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FINAL PROJECT REPORT

OBJECT MOTION ANALYSIS STUDY

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PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

CONTRACT NO. NAS-5-23234

ATTENTION:
J. PANDELIDES/CODE 711

OCTOBER 1974

ELECTRO-OPTICS OPERATION

HARRIS
COMMUNICATIONS AND INFORMATION HANDLING

HARRIS CORPORATION Electronic Systems Division*
P.O. Box 37, Melbourne, Florida 32901 305/727-4000
*(formerly RADIATION)

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This report was prepared by the Electro-Optics Operation of the Electronic Systems Division of Harris Corporation, which is located in Melbourne, Florida. It covers work carried out between May 9, 1973 and September 30, 1974 under Contract No. NAS5-23234. Mr. John Pandelides was contract monitor for NASA, GSFC.

The Principal Investigator and Program Manager was F. B. Rotz. M. O. Greer and K. R. Porter performed a major portion of the work. This effort was carried out in the Systems and Programs Department, Dr. A. Vander Lugt, Director.

ABSTRACT

The use of optical data processing (ODP) techniques for motion analysis in two-dimensional imagery was studied. The basic feasibility of this approach was demonstrated, but inconsistent performance of the photoplastic used for recording spatial filters prevented totally automatic operation. Promising solutions to the problems encountered are discussed, and it is concluded that ODP techniques could be quite useful for motion analysis.

SECTION I

INTRODUCTION

A common problem in data analysis is the extraction of position versus time data for objects in a sequence of photographs or similar images. For instance, one may be interested in determining the instantaneous velocity of various parts of a machine as recorded by cinematography. In the case of imagery obtained by an unmanned spacecraft, there are applications where a relatively small amount of motion information could replace the large amount of data required to transmit entire images. For example, in using a satellite to track ice or cloud motion, appropriate on-board processing would make it possible to transmit only the positions of moving objects (ice or clouds) rather than entire scenes. This would greatly reduce the amount of data transmitted over the telemetry link.

Motion analysis from photographic records can present practical difficulties even under the best of conditions; a number of techniques have been applied to this data reduction problem. Direct human interaction may be used where the amount of data involved is relatively limited. For example, in analyzing highway traffic flow from aerial photographs, a human operator can readily locate the positions of various vehicles in a sequence of frames.

Digital correlation techniques can also be used for motion analysis. In this approach, imagery is scanned, quantized and fed to a computer capable of performing digital cross-correlation. In order to detect the motion of objects, local regions of one input scene are cross-correlated against local regions of another input scene. The location of the cross-correlation peak indicates the relative motion of an object (pattern) common to both regions.

Of course, if several objects are common to both regions but have moved differently, multiple correlation peaks will occur. In order to avoid this ambiguity, the region being correlated must be limited in size to avoid including more than one object of interest (say a cloud, ice flow or vehicle). On the other hand, the range of the cross-correlation must be sufficient to accommodate any reasonable motion. Consequently, it may be necessary to cross correlate a large number of small disjoint regions (the size of objects of interest) in one scene with an equal number of larger overlapping regions in the second scene (the size of the expected correlation range). The number of computations and time required will increase with the range of the cross correlation and the number of regions involved. The total computational problem can become rather awkward where large cross-correlation ranges must be handled. When it is necessary to handle rotation as well as translation, the problem becomes considerably more difficult.

Optical data processing (ODP) offers a means for motion analysis based upon cross correlation. An optical system can be arranged so that its output is a two-dimensional display of the cross correlation between two input transparencies. By limiting the illumination on one of the transparencies to an area containing only one object of interest, the output becomes the cross correlation of this object with the entire other transparency. This technique offers a number of advantages. The cross-correlation is carried out in parallel and instantaneously over the entire scene offering the potential for very high speed operation. Rotation can be handled by rotating a single optical element in the system, and scale variations can also be accommodated. The principal drawbacks of ODP systems are associated with data input and extraction.

This report details our efforts in demonstrating the use of coherent optical data processing for motion analysis. The basic goal of this program

was to demonstrate a totally automatic object motion analysis system based upon coherent optical data processing techniques. The imagery to be analyzed was a sequence of artificial scenes in which various objects appeared in different positions and orientations. An in-house optical data processing system was used in performing the desired cross correlations. The basic feasibility of the process was demonstrated. However, due to the highly inconsistent behavior of the real-time spatial filter recording device used in the system, repeatable, automatic operation was not achieved. The basic cause of the difficulties encountered has been determined and should be amenable to a practical solution.

This report is organized in the following manner. In Section II we discuss the basic principles of coherent optical data processing and present some typical results of cross correlation experiments in motion (position) analysis. In Section III we cover the requirements for an automatic coherent optical system including data input and output as well as real-time spatial filter generation. In Section IV we describe our in-house laboratory optical data processing system. In Section V we detail the experiments performed to demonstrate totally automatic operation using NASA provided imagery. In Section VI we discuss the most promising solutions to difficulties encountered with the real-time filter recording device. Section VII provides our conclusions and recommendations.

SECTION II
CORRELATION TECHNIQUES

GENERAL

The basic principle behind using correlation techniques to measure object motion is that the location of a cross-correlation peak is determined by the relative displacement of the signals being correlated. Consider the cross-correlation, $r(x, y)$, between two functions $f(x, y)$ and $h(x, y)$

$$r(u, v) = \iint_{\infty}^{\infty} f(x, y)\ h(x+u, y+v)\, dx\, dy \tag{1}$$

$$\equiv f * h . \quad \text{(Definition of cross-correlation operation.)}$$

Although both integrals are over infinite limits, it is understood that $f(x, y)$ and $h(x, y)$ are of finite extent.

If the function $h(x, y)$ contains the function $f(x, y)$, $r(u, v)$ will be a maximum at some specific values of u and v. These values can then be used to locate $f(x, y)$ relative to $h(x, y)$.

For example, let us consider two scenes $T_1(x, y)$ and $T_2(x, y)$ showing the same general area, but containing an object $o(x, y)$ which appears at different locations in each scene. Then

$$T_1(x, y) = o(x - x_1, y - y_1) + g_1(x, y) \tag{2}$$

and

$$T_2(x, y) = o(x - x_2, y - y_2) + g_2(x, y)$$

where $o(x-x_i, y-y_i)$ denotes the object centered at point (x_i, y_i) and $g_i(x,y)$ denotes everything else in the scene. Note that $o(x,y)$ and $g(x,y)$ are mutually exclusive. We now assume that the auto-correlation of $o(x,y)$ is approximately a delta function of magnitude A, i.e.,

$$\iint o(x,y)\, o(x-u, y-v)\, du\, dv \cong A\delta(u,v) \quad . \tag{3}$$

Furthermore, let us assume that the cross-correlation of the object with everything else in the scene is small, i.e.,

$$\iint o(x,y)\, g(x-u, y-v)\, du\, dv \approx \varepsilon(u,v) \tag{4}$$

where

$$|\varepsilon| \ll |A| \; .$$

Cross-correlating the functions $T_1(x,y)$ and $T_2(x,y)$ yields

$$\begin{aligned} r(U) &= o(X-X_1) * o(X-X_2) + o(X-X_1) * g_2(X) \\ &\quad + o(X-X_2) * g_1(X) + g_1(X) * g_2(X) \end{aligned} \tag{5}$$

where U and X denote the diades (u,v) and (x,y), respectively. If we limit the input $T_1(X)$ by multiplying it by a "window" or rectangular function centered at X_1 which covers a region only slightly larger than the object $o(X-X_1)$ then the output becomes

$$\begin{aligned} r(U) &= o(X-X_1) * o(X-X_2) + o(X-X_1) * g_2(X) + o(X-X_2) * g_1(X) \\ &\approx A\delta(X_1 - X_2) + \varepsilon(X_1) + \varepsilon(X_2) \quad . \end{aligned} \tag{6}$$

That is, $r(U)$ consists of a peak located at $X_1 - X_2$ plus a general low level background covering approximately the same area as T_2. The location $(X_1 - X_2)$ of the peak is a direct measure of the relative displacement of the object $o(x)$.

An important feature of this operation is that it is not necessary to define a specific pattern $o(X)$ (e.g., a vehicle) but merely to isolate it by selecting limited regions throughout the domain of $T_1(X)$. Of course it is possible that spurious correlation peaks (false alarms) may arise if the selected region $o(X)$ is sufficiently similar in appearance to other regions in $T_2(X)$. The region sampled at any one time must be large enough to be unique but it must not be so large as to contain a number of patterns each of which may be displaced in a different manner. The optimum sampling area is dependent upon the nature and resolution of the scenes involved.

COHERENT OPTICAL CORRELATION TECHNIQUES

Both incoherent and coherently illuminated optical systems have been used to evaluate the correlation function $r(u, v)$ as given in Equation (1). The arrival of CW gas lasers as powerful and economic sources of spatially and temporally coherent light make coherently illuminated systems practical and the clear choice over incoherently illuminated systems. Their superiority arises from their ability to display the Fourier transform of a two-dimensional input function so that the transform can be modified by a spatial filter and the corresponding filtering operation effected simultaneously over the entire input function. The undesirable bias term that appears at the output of incoherently illuminated

systems is easily eliminated in coherent systems by rejecting these portions of the Fourier transform representing low frequency components of the input function.

Figure 1 shows the basic elements of a coherent optical data processing system. In describing the operation of the system we shall assume that photographic transparencies are used to input the data and for recording filters. Later we will discuss how this constraint may be removed. A point source of monochromatic light, collimated by lens L_c, illuminates $f(x, y)$ which is one frame of imagery. A spherical lens L_1 displays the two-dimensional Fourier transform $F(p, q)$ of $f(x, y)$ at its back focal plane P_2. Although the Fourier transform relationship exists for a wide range of axial positions of $f(x, y)$, the optimum position of $f(x, y)$ is at the front focal plane of L_1. A spatial filter having the transmittance $T(p, q)$ can be placed in plane P_2 to modify $F(p, q)$ directly. If we apply the convolution theorem to Equation (1), we find that

$$r(u, v) = \frac{1}{4\pi^2} \iint_{-\infty}^{\infty} F(p, q) H^*(p, q) e^{-j(pu+qv)} dp dq \tag{7}$$

where $H(p, q)$ is the Fourier transform of the stored reference function, * denotes conjugate, and p and q are spatial frequency variables related to the space coordinates (ξ, n) in plane P_2 by the relationships

$$p = \frac{2\pi\xi}{\lambda F_1}, \quad q = \frac{2\pi\eta}{\lambda F_1}, \tag{8}$$

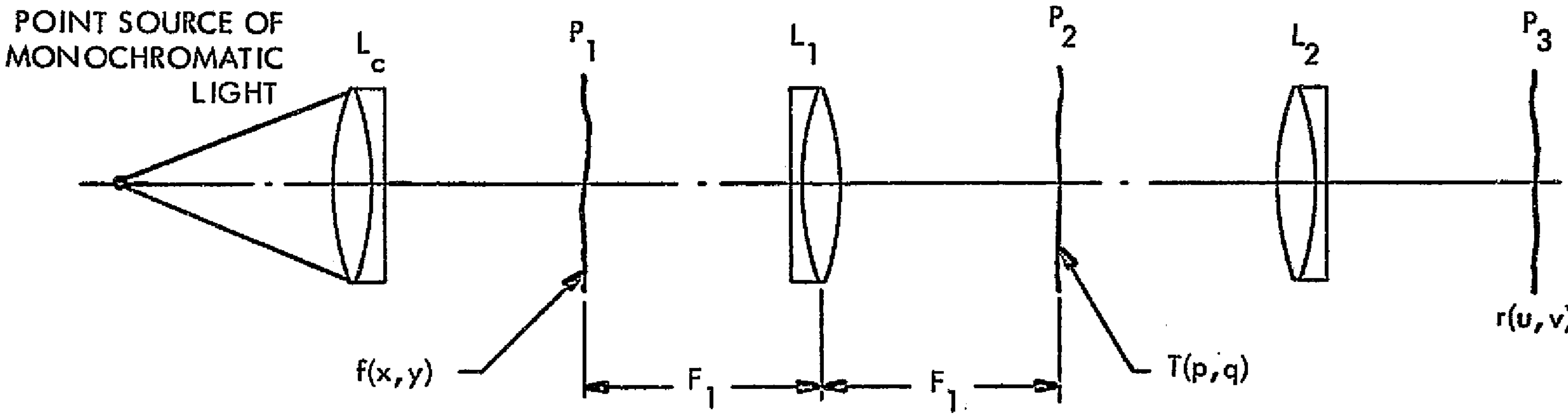


FIGURE 1. OPTICAL CORRELATOR

where λ is the wavelength of the illumination and F_1 is the focal length of L_1. Equation (7) shows that the appropriate filter function $T(p,q)$ to be placed in plane P_2 is the conjugate of the Fourier transform of the stored reference function. The cross-correlation function $r(u,v)$ is then formed by a second Fourier transform; lens L_2 is used for this purpose.

The required filter function $H^*(p,q)$ can be constructed by using spatial carrier-frequency filters.[1] Figure 2 shows a filter-generator in which $h(x,y)$ is placed in plane P_1 and illuminated by a plane we have of monochromatic light. Lens L_1 displays the Fourier transform $H(p,q)$ at its back focal plane. A reference beam of light, denoted by $A\exp[jpb]$, is added to $H(p,q)$ and the intensity of the sum of these two light beams is recorded on a high resolution photographic film such as Kodak 649F. The light intensity at plane P_2 is

$$\begin{aligned}|G(p,q)|^2 &= |A e^{jpb} + H(p,q)|^2 \\ &= A^2 + |H(p,q)|^2 + A e^{-jpb} H(p,q) + A e^{jpb} H^*(p,q) \qquad (9)\end{aligned}$$

where $b = F_1 \tan a$.

Because a coherently illuminated optical system is linear in light amplitude, we want to relate the amplitude transmittance of the recorded filter to the incident exposure. We characterize the linear portion of the amplitude transmittance versus exposure curve of a film by

$$T_a = T_0 - \beta E, \qquad (10)$$

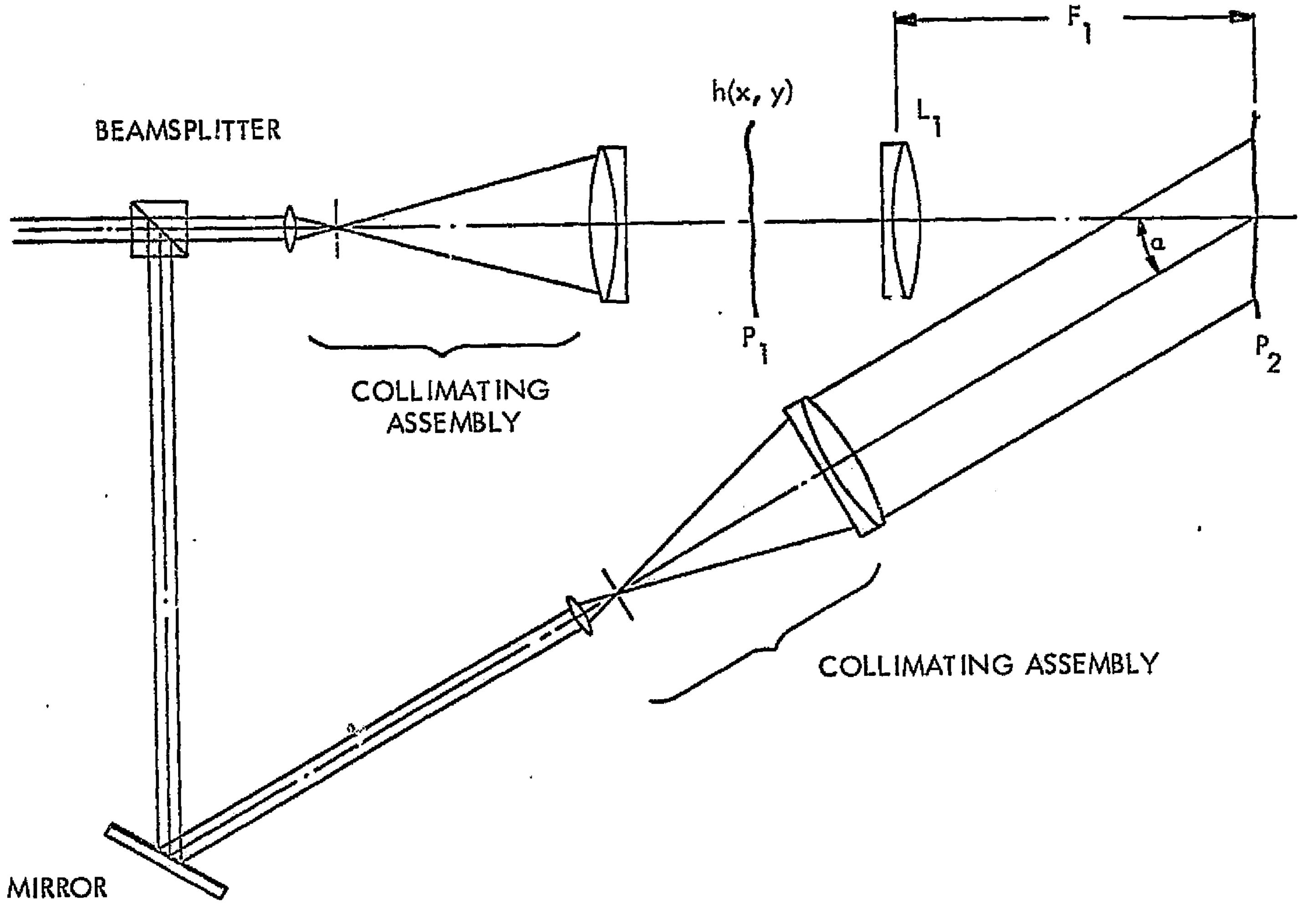


FIGURE 2. SPATIAL FILTER RECORDING SYSTEM.

where T_0 is the amplitude intercept and β is the slope of the straight line. By substituting Equation (9) into Equation (10), we have

$$T_a(p,q) = T_0 - \beta t \, |G(p,q)|^2 , \tag{11}$$

where t is the time duration of the exposure. We now expand $|G(p,q)|^2$ and collect terms to get that

$$\begin{aligned} T_a(p,q) &= T_0 - \beta t \left\{A^2 + |H(p,q)|^2 + A\,e^{-jpb} H(p,q) + A\,e^{hpb} H^*(p,q)\right\} \\ &= \beta t \left\{(A^2 - T_0/\beta t) + |H(p,q)|^2 + A\,e^{-jpb} H(p,q) + A e^{jpb} H^*(p,q)\right\}. \end{aligned} \tag{12}$$

Note that the last term of Equation (12) contains the desired filter function $H^*(p,q)$; it remains to be shown that this term can be separated from the others.

After exposure and development, the filter $T_a(p,q)$ is placed in plane P_2 of the optical system shown in Figure 1 and is illuminated by $F(p,q)$. At the output plane P_3 of the processor we observe three filtered versions of the input data:

$$r_1(-u,-v) = \frac{1}{4\pi^2} \iint_{-\infty}^{\infty} F(p,q) \left[(A^2 - T_0 \beta t) + |H(p,q)|^2 \right] e^{-j(pu+qv)} \, dpdq$$

$$r_2(-u,-v) = \frac{A}{4\pi^2} \iint_{-\infty}^{\infty} F(p,q) \, H(p,q) \, e^{-j[p(u-b)+qv]} \, dpdq$$

$$r_3(-u,-v) = \frac{A}{4\pi^2} \iint_{-\infty}^{\infty} F(p,q) \, H^*(p,q) \, e^{-j[p(u+b)+qv]} \, dpdq \, . \tag{13}$$

The first term of Equation (13), centered upon the optical axis, is generally of no interest. The second term, centered at $u = -b$, represents the convolution of $f(x, y)$ with $h(x, y)$. The third term, centered at $u = +b$, represents the desired cross-correlation of $f(x, y)$ and $h(x, y)$. If we bear in mind that $r_3(-u, -v)$ is centered at $+b$, we may rewrite the third term as

$$r_3(-u, -v) = \frac{A}{4\pi^2} \iint_{-\infty}^{\infty} F(p, q)\, H^*(p, q)\, e^{-j(pu + qv)}\, dp\,dq \qquad (14)$$

which is identical to the desired operation as given by Equation (7) and, through the use of the convolution theorem, is identical to Equation (1). The coordinates (u, v) in plane P_3 have reversed signs as a consequence of the fact that a positive spherical lens always introduces a negative kernel function in the Fourier transform operation. The negative coordinates imply that the filtered image is rotated through π radians, a natural result obtained from any imaging system whether coherently or incoherently illuminated.

So far we have assumed that the film which records the filter function is linear; all recording materials are, of course, linear only over a certain range of exposures. If the film were linear, we could disregard the presence of the $|H(p, q)|^2$ term in Equation (9). We shall now show that this term and the nonlinearity of the film can be used to good advantage in optimizing the bandpass characteristics of the spatial filter. The effects of film nonlinearities on spatial filters has been studied in detail and has led to the use of a technique called transposed processing. The details of transposed processing will not be given here (an abridged account can be found in Reference 2); we shall give, rather, a heuristic argument to illustrate its application.

Both the stored reference function $h(x, y)$ and the input imagery $f(x, y)$ contain an average value (or bias) term which contains no information about the structure or texture of the imagery. It is advantageous, therefore, to suppress this term and other low frequency components so that the cross-correlation is based upon the higher spatial frequencies which bear the information about the detailed texture of the imagery. This suppression is accomplished by controlling the amplitude A of the reference beam and the time duration t of the exposure. The value of A is set so that $A^2 << |H(p, q)|^2$ at low frequencies, causing the exposure modulation level to be small. The value of t is chosen to cause the film to saturate where $|H(p, q)|^2$ is large. This produces a spatial filter which is highly edge sensitive and has relatively little response to low frequency tonal characteristics of the imagery.

By properly selecting the exposure and the ratio of reference beam to signal beam intensities (K-ratio), we can optimize the spatial bandpass characteristics of filters for a particular application. In general, the lower the K-ratio, the greater will be the filter's sensitivity to orientation and it's discrimination between similar patterns. If a filter is made too edge sensitive (very high passband), even slight differences between two images of the same object may severely degrade the resulting correlation. On the other hand, if a filter is made so as to have strong response near zero spatial frequency, it will produce broad, less well defined correlations. It will be less discriminating between similar patterns and will produce more false alarms. Typically, empirical means are used to establish the optimum spatial filter recording parameters for specific applications.

In the case where we are attempting to determine motion by cross-correlating two sequential frames, we can assume that the same object will look the same in both frames. Hence, we can use a relatively high bandpass, edge-sensitive filter which will yield a correlation which is well defined both in position and orientation.

ROTATION AND SCALE

The correlation operation is sensitive to both the relative scale and orientation of the scenes being correlated. The degree of sensitivity is a function of the patterns involved; e.g., a circle shows scale sensitivity but no orientation sensitivity. The correlation of a long rectangular object is highly orientation sensitive. In many cases it is necessary to handle scale and orientation differences between the pattern used in making a filter and the input being correlated. Both of these capabilities can be incorporated into an optical data processing system.

Orientation can be handled by several means: rotating the input scene about the optical axis, rotating the filter about its center or using an image rotating prism or mirror assembly to effectively rotate the input relative to the filter. The most practical method is to use an image rotating prism, such as a Pecham prism, placed between the input and filter planes. Simply rotating this prism will cause the apparent input to rotate relative to the filter. Physically rotating the input may also be a reasonable approach depending upon the form of the input data; e.g., a fairly elaborate mechanism may be required to rotate large rolls of film. Rotating the filter is generally undesirable because this causes the output correlation plane to swing in an arc about the optical axis.

Scale variation may be implemented as shown schematically in Figure 3. The most important feature of this optical system is that the input plane P_1 is located in a convergent beam of light. It can be shown that this system creates the Fourier transform in the plane of focus P_2 of the lens L_0 but the scale of the transform is determined by the distance ℓ between the input plane P_1 and the Fourier plane P_2 . The system is arranged so that the lens L_2 moves with the input P_1 and the distance between the input and the output plane P_3 remains constant. This is precisely the relationship desired, since we wish to vary the size of the transform with respect to a fixed filter. The image plane P_3 will contain the cross-correlation of the input (in plane P_1) and the image from which the filter was made even if the distance ℓ is not fixed at the same value as was used when making the filter. The input plane can be moved axially to change the scale of the Fourier transform and the image plane will contain a valid cross-correlation; however, the relative scales of input and filter function will be changed.

EXAMPLES OF MOTION ANALYSIS

The basic principle of using spatial filtering for motion analysis is shown in Figure 4. This figure shows a coherent optical processing system with an input transparency containing a number of patterns (e.g., clouds, cars, etc.). The spatial filter in the system was made in the usual manner from another transparency containing the same patterns but possibly at different positions. A portion of the input is illuminated; the size of the illuminating beam is approximately equal to

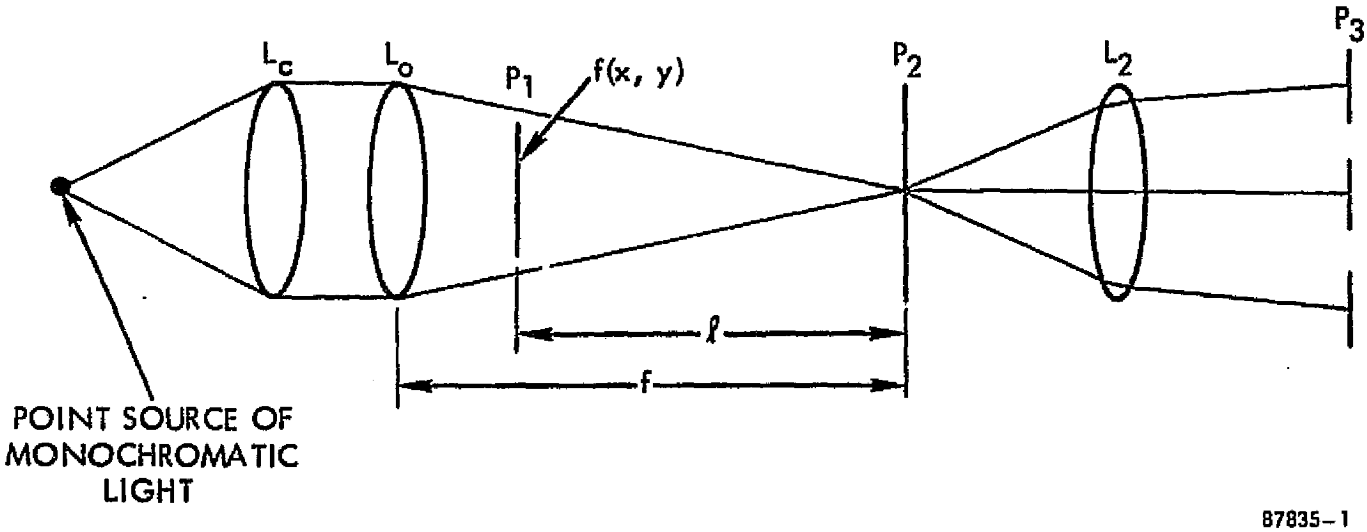


FIGURE 3. VARIABLE SCALE SYSTEM.

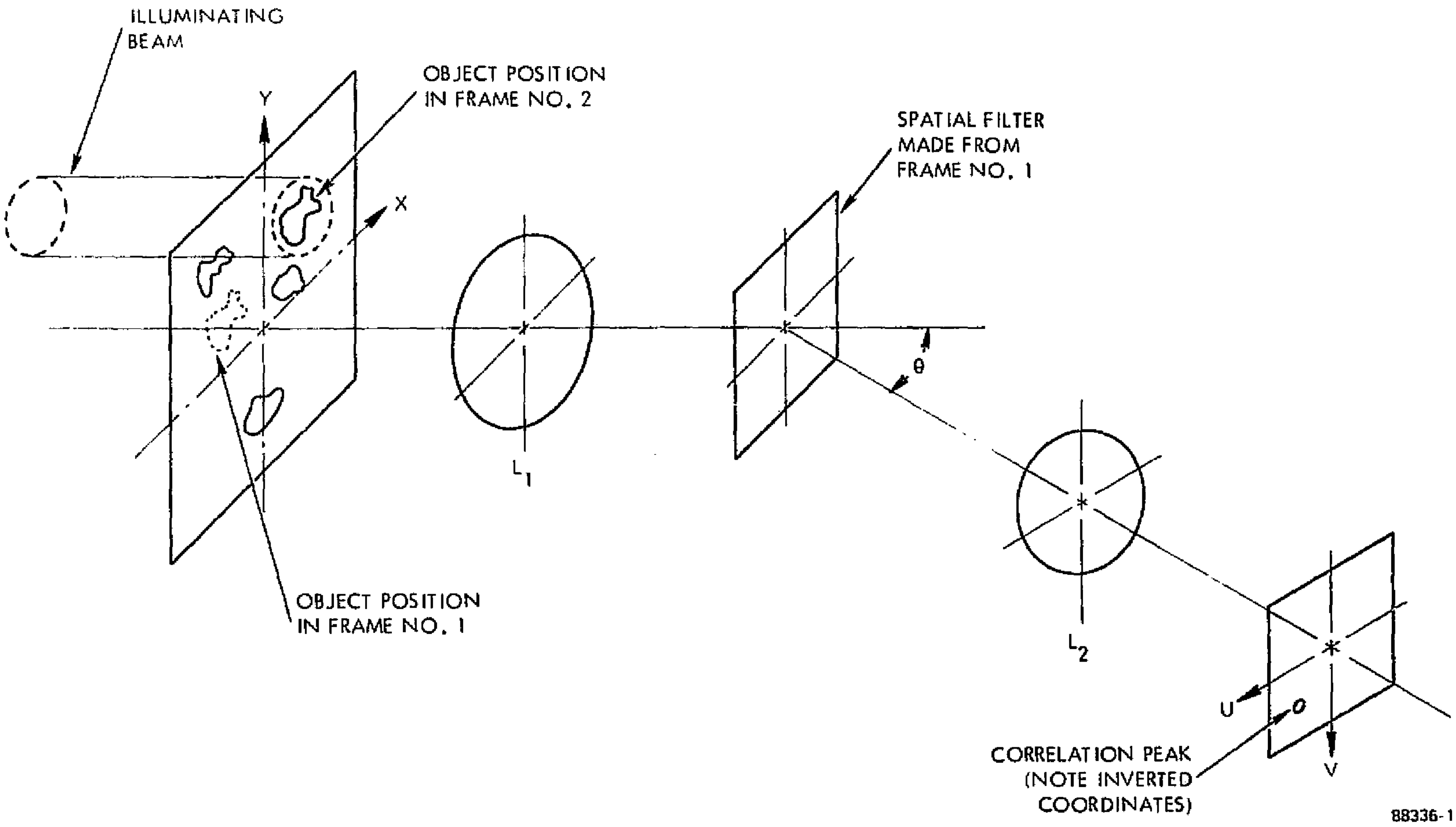


FIGURE 4. MOTION ANALYSIS BY MEANS OF OPTICAL CROSS-CORRELATION.

the size of objects of interest. The output plane of the system contains the cross-correlation of the illuminated region of the input with the entire scene from which the spatial filter was made. This correlation contains an intensity peak representing the auto-correlation of the desired pattern and located at a position corresponding to the relative displacement of the pattern from the first transparency to the second.

An example of using optical data processing to determine the relative displacement of two frames of imagery is shown in Figure 5. A spatial filter was made from a portion (Figure 5c) of frame 5a. This filter was used in the optical system with input 5a producing the auto-correlation shown in 5d. When input 5b was placed in the input of the system, the cross-correlation shown in 5e was produced. Note that correlation peaks in d and e are displaced relative to each other in exactly the same manner as the input scenes. An interesting feature of this particular example is that the filter was recorded on a real-time photoplastic device.

Experiments have been performed using a coherent optical system to measure cloud motion. Imagery obtained by a geosynchronous satellite (ATS III) was used in this experiment. A spatial filter was made from a particular frame of imagery (23 April 1968, Frame 21GC) and positioned in the frequency plane of the optical system. Frames of cloud imagery obtained approximately 30 minutes and one hours later (frames 23GC and 25GC) were placed sequentially in the input plane of the optical system. A small aperture was positioned at various locations in the input plane to illuminate particular clouds or portions of cloud formations. The location of the peak of the

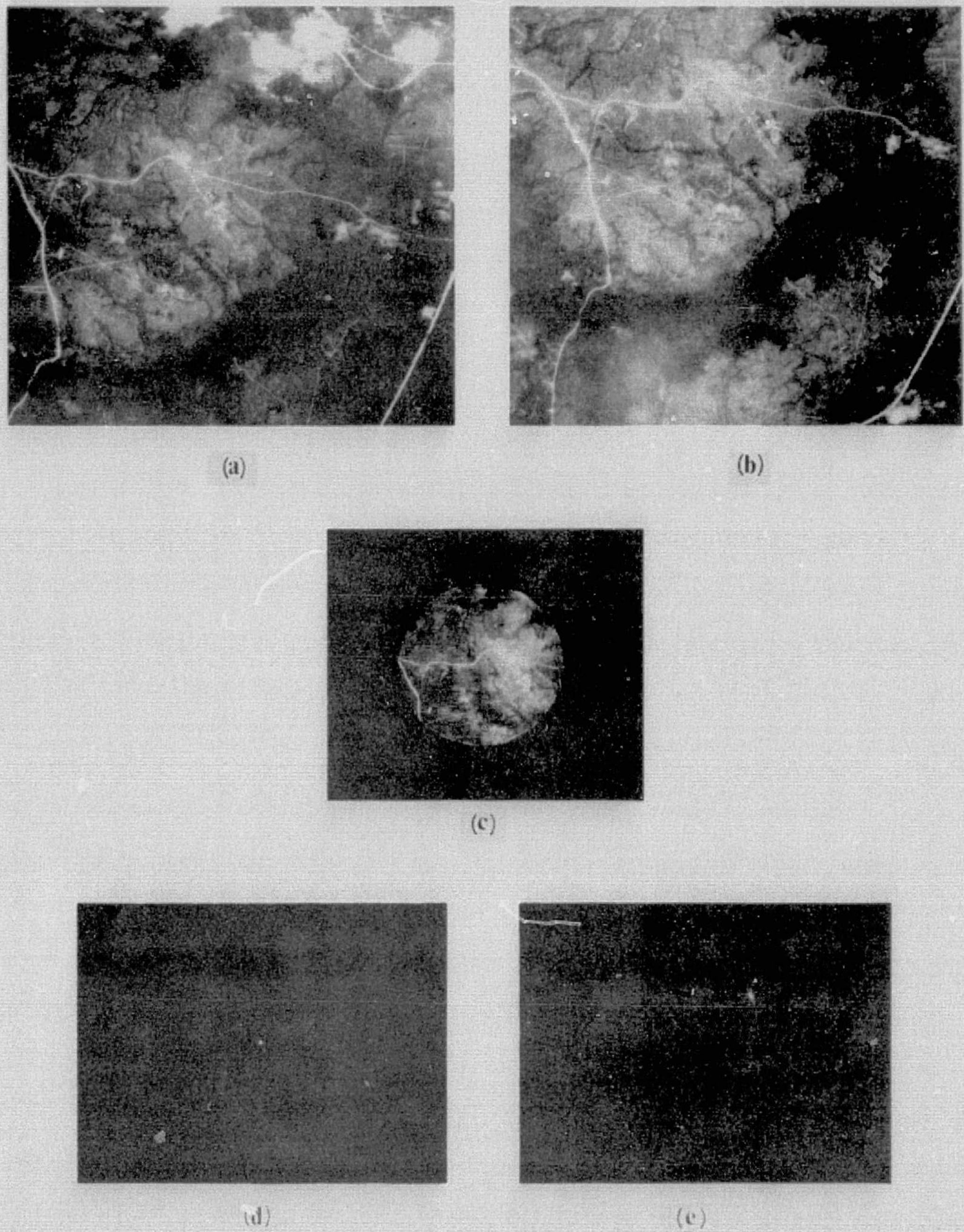


FIGURE 5. CROSS-CORRELATION TO DETERMINE THE RELATIVE POSITIONS OF TWO SCENES (PHOTOPLASTIC FILTER).

cross-correlation in the output plane was measured by visually positioning the crosshairs in a microscope and reading a pair of micrometers. About thirty separate regions were investigated and a majority of these produced well defined correlation peaks.

In some cases, clouds did not produce measurable correlations. This was probably due to significant changes in their shape between frames or a lack of contrast and detail. As would be expected, the pictures obtained 30 minutes apart produced more and better defined cross-correlations than did the pictures taken one hour apart. The visible land features were of such low contrast that they did not produce any measurable correlation peak. Consequently only relative cloud displacement can be inferred from the data.

Figure 6 shows the scene from which the spatial filter was made. The Baja, California, penninsula and portions of Mexico and Central America are visible. Figure 7 shows velocity vectors plotted by computer from data obtained in this experiment. In these figures the location of a particular area is marked by a cross and a number. The relative velocity (not displacement) of the clouds in each area is indicated by a line originating at the cross and terminating at the center of the square or diamond shaped symbol. The squares and diamonds indicate data for time intervals of 30 minutes and one hour, respectively.

The numbered circles in Figure 6 shows the locations of the various cloud regions while each division on the N-W axis in Figure 7 represent approximately 25 mph. The variable geometry of the scene has not been considered in determining velocities.

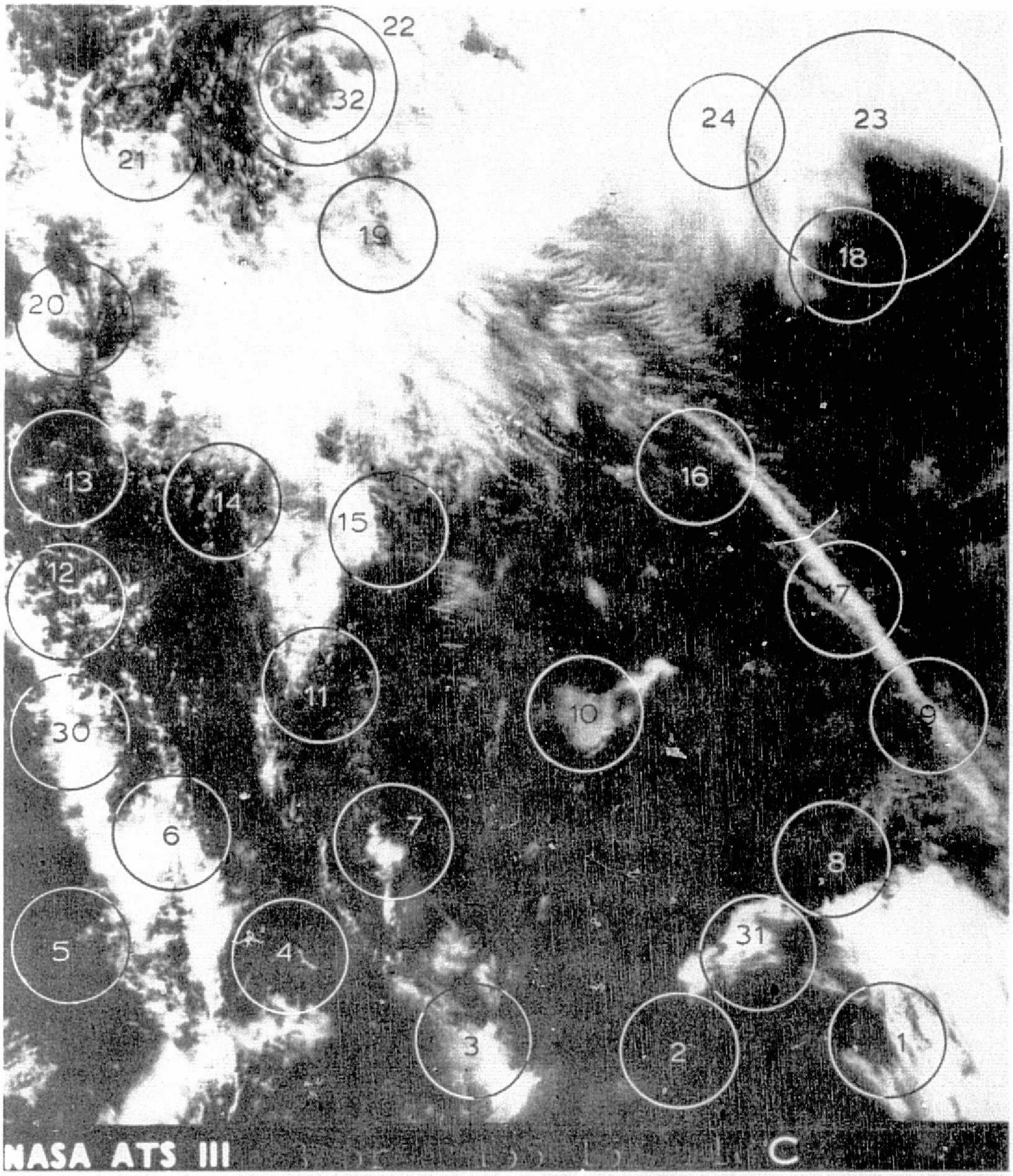
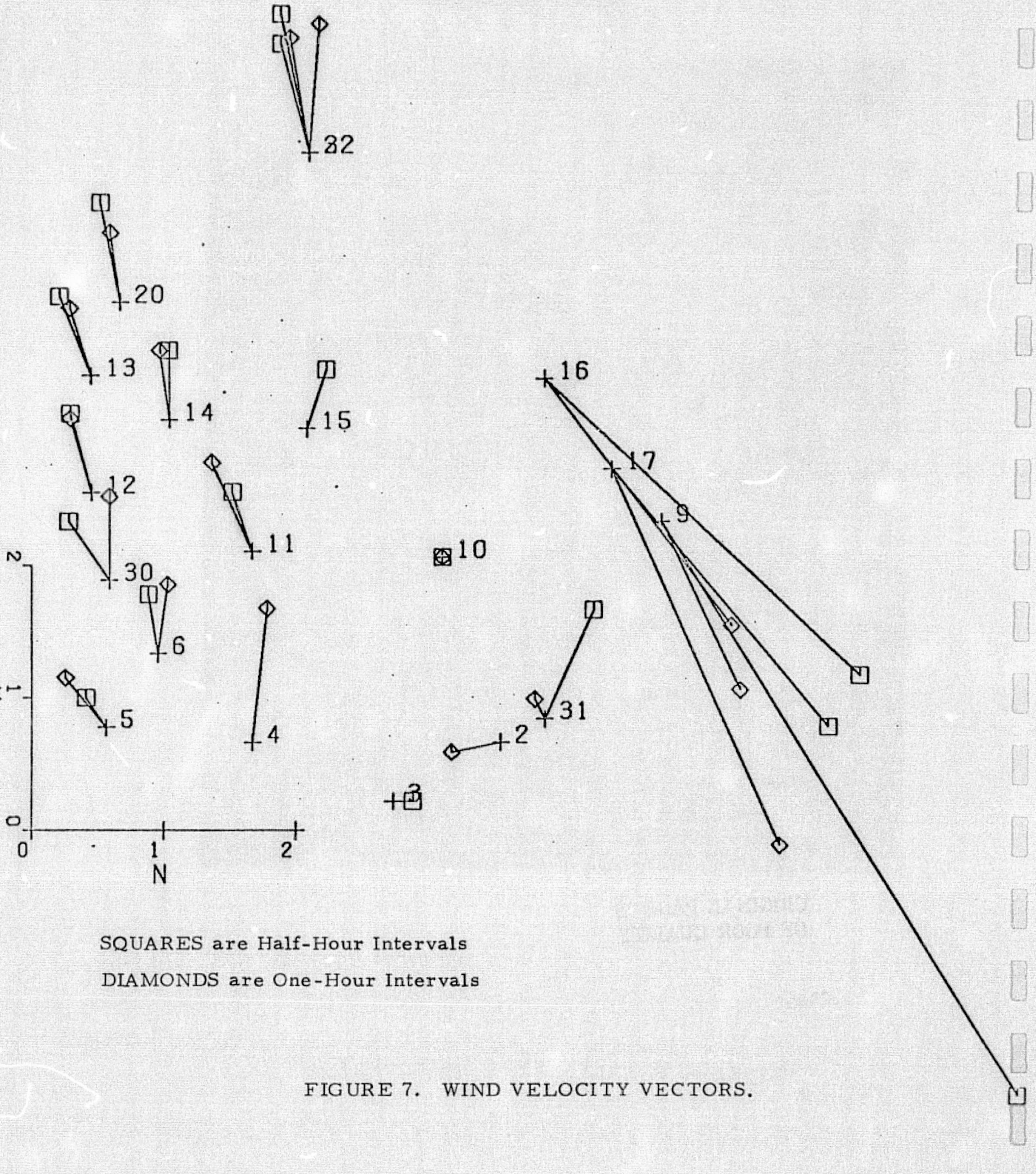


FIGURE 6. SATELLITE CLOUD PICTURE.



SQUARES are Half-Hour Intervals

DIAMONDS are One-Hour Intervals

FIGURE 7. WIND VELOCITY VECTORS.

Figure 8 shows the appearance of the correlation peaks in the output of the system for satellite pictures obtained 30 minutes apart. Most of the desired correlations appear as well defined bright spots; however, the long streamer-like cloud in region 17 produced an elongated correlation. peak. Correlations produced by these regions in pictures obtained one hour apart are quite similar in appearance, except that the correlation for region 17 which became even more elongated.

AREA NO. 32

AREA NO. 17

AREA NO. 30

AREA NO. 11

AREA NO. 14

AREA NO. 10

FIGURE 8. CLOUD CROSS-CORRELATIONS: HALF HOUR INTERVAL.

SECTION III

REQUIREMENTS FOR AN AUTOMATIC OPTICAL DATA PROCESSING SYSTEM

The features required in an optical data processing system are strongly influenced by the intended application. In general, there must be a capability for data input, filter generation, and correlation data readout. Moreover, there may be a requirement for orientation or scale variation.

DATA INPUT

The most commonly used means for data input to an optical processor are photographic transparencies. In many applications this is quite acceptable; however, there are also numerous interesting cases where the use of photographic inputs is too slow, awkward or in some other manner unacceptable. Several general requirements for a data input device can be established; these and some promising devices are discussed below.

A data input device must be able to modulate a beam of coherent light either in phase or amplitude in a manner dictated by the data rather than the device itself. That is, the device must not significantly distort the (phase or amplitude) modulation due to data. For example, an amplitude transparency must usually be immersed in an index matching liquid in a gate with optically flat windows to eliminate phase perturbations caused by thickness variations in the transparency. Similarly, a diffuse reflector, such as a printed page, cannot be used directly as an input to a coherent optical system because of the random phase created by the rough surface of the paper.

In most cases, an input device must contain a large number of resolution elements, say 10^3 to 10^6 or more. If this is not the case, one

of the major advantages of an optical processor -- its ability to handle a large quantity of data simultaneously -- does not apply and it may be more effective or simple to use electronic or digital correlation techniques.

The input device must be capable of handling the desired input data rate and format. Typically a megabit/second rate or greater may be required. By way of comparison, a typical TV picture uses a 5 MHz bandwidth while a 35 mm format snapshot made in 0.01 seconds represents about 3.5×10^8 pixels/second. (Note that if we assume 16 shades of grey, each pixel requires 4 bits for definition.)

There are presently a number of candidate devices for data input. These include thermoplastics, the PROM[3] (Pockels Readout Optical Modulator), Ferrpic, Cerampic, and other devices employing optically active crystals or materials. These devices are extensively discussed in the literature[4] and we will limit our attention to two of the more promising, thermoplastics and the PROM.

The PROM consists of a single active layer of a cubic photosensitive, electro-optic material one or both sides of which are coated with a transparent insulator and a transparent conductor. A high potential is applied to the transparent conductors, creating a potential gradient through the device. If a region of the active material is illuminated, charge carriers are generated which travel through the crystal and locally reduce the electro-optic voltage. After reading (exposure) the transparent electrodes are shorted together reducing the electric field in the unexposed regions to zero. However, charge carriers are trapped at the surface of the crystal in the exposed regions and produce a local electro-optic voltage across the crystal.

For readout, the device is illuminated by polarized light whose plane of polarization bisects the crystal's birefringent axes. The light passing through the crystal becomes elliptically polarized to an extent determined by the local electro-optic voltage and hence determined by the local exposure. A cross polarizer at the output of the device converts this polarization effect into an intensity modulation. The active material (typically ZnSe or $Bi_{12}SiO_{20}$) is considerably more sensitive to blue than to red light. Hence, exposure is made with blue and readout is done with red light.

PROM devices have been reported with areas of over 2 cm^2, resolution of 300 lpmm, and contrast ratios of 5000 to 1. They can be recycled quickly, possibly in as little as one millisecond, and they have a relatively long storage time in the dark. Their reported characteristics seem quite desirable for use as an input device; their present resolution is rather low for efficient use in recording spatial filters.

Photoplastics and thermoplastics are also an attractive means for data input to a coherent optical system. In this case a light intensity distribution (photoplastics) or the current density of a scanning electron beam (thermoplastics) is converted to a thickness variation (surface relief) in a thermoplastic layer. Light passing through this layer is phase modulated in a manner corresponding to local thickness. These devices have high resolution (over 1000 lpmm) and can be recycled. Input modulators employing a thermoplastic layer with electron beam writing have achieved writing rates of up to 50 MHz. Photoplastic devices are relatively simple and inexpensive to fabricate, and, where high recycling rates are not required, they may be quite useful. Photoplastic devices will be considered more extensively in a later section.

DATA SCANNING

The size of the scanning aperture or beam used to define the area being correlated is important. If it is too large, multiple correlations may result from several objects, moving in different ways, being illuminated simultaneously. On the other hand, if it is too small, correlation signal-to-noise ratio will be reduced and numerous false alarms may result. The optimum size for the scanning beam is dependent upon the nature of the scenes expected. However, it will usually be desirable to use the minimum aperture which will cover approximately 100 x 100 resolution elements. This will typically provide strong correlations with good discrimination. In cases where widely separated objects are expected, a larger aperture may be used. This will reduce the number of locations which must be correlated.

SPATIAL FILTER GENERATION

The resolution requirements for the media used to record a spatial filter are much more severe than those associated with data input. This is clear from the fact that the filter itself must have a spatial frequency bandwidth comparable to that of the input data plus the carrier frequency introduced by the reference beam. Typically, response to at least 1000 lpm is desirable. A spatial filter can be recorded in either an absorption or phase material.

The ideal filter recording media would be usable (exposure and development) in real time and reusable. Self developing materials such as photopolymers can be used for recording holograms; however, they are not reusable. Normally available self-developing materials such as photochromics are so insensitive that generally they are not practical for use as spatial filters.

Photoplastic devices have been used for recording holograms and spatial filters and possess several desirable features. They have adequate sensitivity, high resolution, are reusable and are relatively simple and inexpensive to fabricate. Moreover they can be completely controlled by electronic signals and hence are compatible with automatic control. At present, photoplastics appear to be among the best available methods for real-time spatial filter recording. A specific photoplastic system will be discussed extensively in later sections of this report.

DATA READOUT

Data readout in the output plane of a coherent optical correlator is essentially the problem of identifying and locating a small, intense correlation peak. Some of the characteristics required of the readout system are determined by the nature of the input data and the application.

The desired auto-correlation peak may be quite small in spatial extent and considerable amounts of undesired cross-correlations (noise) may also be present. The size of the auto-correlation peak is determined by the resolution of the input data and the bandpass characteristics of the spatial filter; it may approach the diffraction limit of the optical system in size. In order to preserve the signal-to-noise ratio (SNR) generated by the optical correlator, it is necessary that the resolution of the output sensor be equal to or better than the size of the expected correlation peak.

The domain over which the correlation can occur is important because it, coupled with the resolution required, determines the total number of resolution elements required in the sensor. In the worst case, the capacity of the sensor would have to equal the space bandwidth product of the optical system.

In many cases, exact knowledge of the location of a correlation peak is not required. For instance, in character recognition a correlation peak will be about as large as the fine details in the characters. However, its location may only need to be known to a precision approaching the size of an entire character. In such cases, a considerable savings in the bandwidth of the data readout system can be effected if correlation locations are reported with the minimum precision required by the application. In general, this requires a non-linear step -- a decision -- between the high resolution sensing of the light distribution and transmission of location data. A readout system satisfying these conditions is discussed subsequently in this report.

ROTATION AND SCALE

Many interesting applications involve situations where the scale and/or the orientation of the input data must be varied. If a suitable input data composer is available, it may be possible simply to rewrite the data at all desired scales and orientations. Otherwise optical and/or mechanical means must be employed.

Rotation can be effected by means of actually rotating the input scene or by use of an image rotating prism such as a Pecham prism. Scale can be varied by arranging the optical system to operate in a so-called "convergent" manner. This is described in Section II and requires fairly straightforward electro-mechanical implementation.

SYSTEM CONTROL

The complexity of the overall control system for an automatic optical correlator is, of course, dependent upon the devices comprising the processor and the application involved. In general, a relatively small minicomputer or

even microcomputer should have the capacity for providing the basic control functions. Interfacing between system devices and the computer is usually straightforward. The software required for control of a basic system should be relatively modest.

SECTION IV

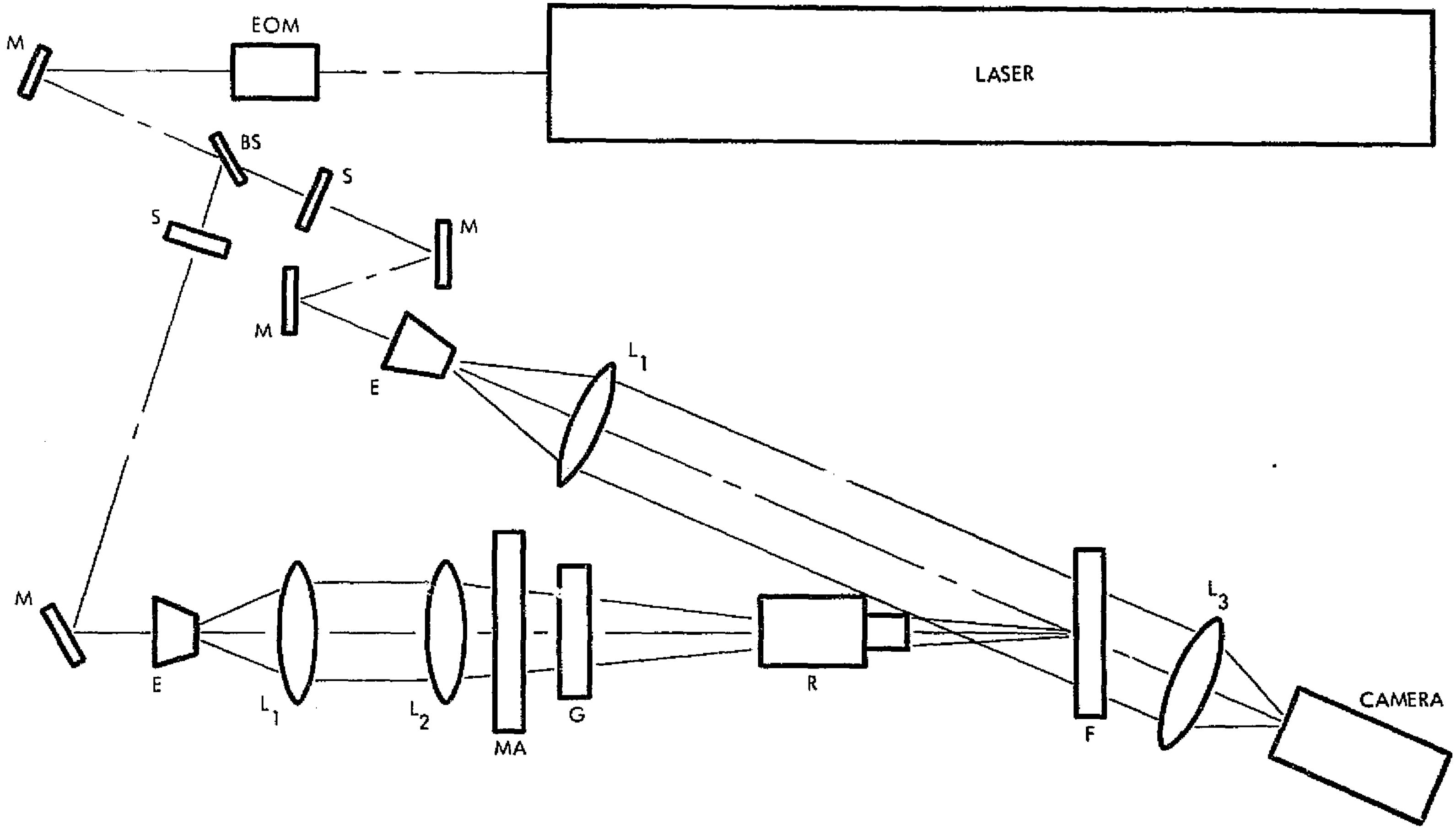
LABORATORY SYSTEM AND EQUIPMENT

The Electro-Optics Operation of Harris Corporation has a laboratory optical data processing system capable of a large degree of automation. We have available a variety of optics and devices to meet a range of applications. The general system and some of the major devices are described below. Particular emphasis is given to photoplastics which we have used both for data input and spatial filter recording.

GENERAL

The laboratory system consists of an optical system containing a variety of devices controlled by a minicomputer. The optical system is shown in Figure 9 which shows the light from a 50 mw HeNe laser split and expanded into a signal beam and reference beam. The reference beam is 100 mm in diameter and focused onto the output sensor which is usually an image orthicon TV system. The signal beam is expanded to 125 mm in diameter and passes through the input, which is usually held in a liquid gate (G). During processing a computer-controlled moving aperture (MA) is also placed in the signal beam.

An image rotator (R) is placed between the input gate and the filter plane. This rotator is a large, modified K prism whose orientation can be controlled by the minicomputer. Several different devices may be used in the spatial filter plane (F); these include a slide camera, precision film drive and photoplastic device.



BS	- BEAM SPLITTER (POLARIZING)	L_1	- COLLIMATING LENS
E	- BEAM EXPANDER	L_2	- FOURIER TRANSFORM LENS
F	- SPATIAL FILTER	L_3	- IMAGING LENS
G1	- LIQUID GATE	M	- MIRROR
EOM	- ELECTRO-OPTIC MODULATOR	R	- IMAGE ROTATOR
MA	- MOVING APERTURE	S	- SHUTTER

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FIGURE 9

DATA INPUT

Four devices are available for data input; a 5" and a precision 70 mm liquid gate, both with roll film drive, a single frame liquid gate and a photoplastic device. Both of the roll film gates use air knives and recirculating index matching fluid to provide dry film in -- dry film out. The precision 70 mm film drive uses a pin registration to locate frames to about 20μ. Film can be moved in either direction by computer or manual command. This gate was used for data input during this study.

The photoplastic device used for data input is essentially the same as that used for recording spatial filters, except that the thermoplastic layer is thicker in order to extend its bandpass to lower frequencies. All functions of the photoplastic can be controlled either manually or by the computer. Very good resolution and apparent grey scale (Schlieren) have been achieved using photoplastic to copy actual aerial photographs for a related study.[6]

The ratio of the light intensities in signal and reference beams is controlled by an electro-optic modulator-polarizing beam splitter combination. The modulator, in response to a command from the computer, rotates the plane of polarization of the laser light. The angle of the plane of polarization in turn determines the ratio of the light transmitted to the light reflected by the polarizing beam splitter. This method has the advantage of high efficiency and easy compatability with electronic control.

FILTERS

Three devices are used for recording spatial filters. The first is a precision slide camera which holds 2" x 12" x $\frac{1}{4}$" microflat photographic plates. Normally 649F emulsion is used. This camera records six filters spaced equidistant along the plate. The filters are selected manually. The slide camera is commonly used where a limited number of fixed filters are required.

The 70 mm precision film gate can also be used for recording filters. Its frame location accuracy satisfies the stringent requirements for properly centering filters. This device is practical when a fairly large number of filters is involved.

Filters can be recorded in real time using a moving wand type photoplastic holder. This mechanism provides uniform charging for an area of 25 x 25 mm^2. The active area of the photoplastic typically employed ranges from 10 x 10 to 20 x 20 mm. All heating and charging signals can be provided either manually or under computer control. We have had considerable success in using photoplastic for recording filters, but as will be discussed in Sections V and VI, some problems remain. Because of their

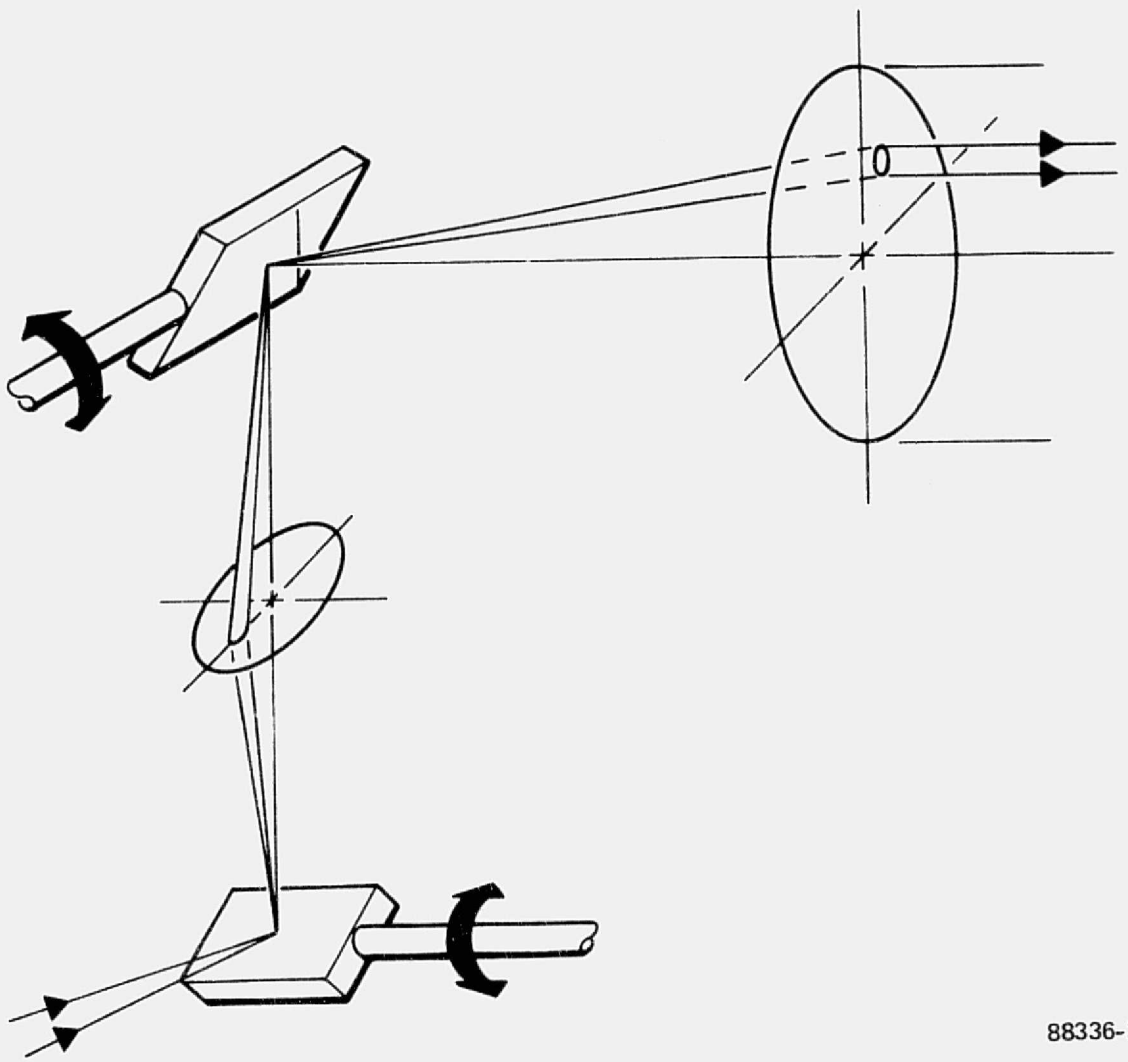

FIGURE 10. TELECENTRIC SCANNER.

called a cell generator. The TV chain serves as an optical-electrical transducer whose video signal is thresholded and organized by the cell generator; the resulting binary data is transmitted directly into the core memory of the computer. The overall operation of the system produces an M x N ($M \le 256$, $N \le 64$, $MN \le 2048$) array of words in the computer memory with values corresponding to the maximum light intensity in an M x N array of rectangular regions at the output of the optical system. This data then describes the brightest peak within each of the MN regions, not the average value of light intensity within a region.

This mode of operation is desired because, although we need high resolution to detect cross-correlation maxima in the output of the optical system, we usually need to locate these maxima only to within some specified precision. In applications such as optical character recognition or tactical target detection, the desired signals have a certain minimum spacing between centers and it is necessary to locate these signals to a precision on the order of this spacing. However, the light distribution indicating a correlation will be a small intense peak whose dimension approaches the maximum resolution of the optical system. To distinguish such peaks from less intense but broader light distributions, we must make the actual light intensity measurements with a high resolution device. Once the measurement of the true maximum intensity has been made, that peak need be located to a precision dictated by the particular application involved. This reduction in precision is a significant data reduction step.

SOFTWARE

The basic software available on the system provides control for the following: shutters, beam intensity ratio control (electro-optic modulator),

moving aperture, position of the 70 mm input gate, image rotator, photoplastic charging and heating, and the readout system. The handlers for these various devices were incorporated as subroutines in FOCAL, a language commonly used on the Digital Equipment Corporation's family of PDP-8 minicomputers. FOCAL is an interactive, table-driven programming language with versatile self-editing capabilities. In actual practice this modified version of FOCAL has proven to be a powerful and convenient means for both automatic and interactive control of the laboratory optical processor.

SECTION V

EXPERIMENTAL EFFORT

This study was essentially an experimental effort to demonstrate automatic measurement of object motion by means of coherent optical data processing. Our laboratory processor was used to perform all of the experiments. Film strips showing simulated scenes as might be obtained from a space craft were used as input. Initial adjustments of some system parameters was allowed, but thereafter the system was to run automatically, inputting new data, making filters and collecting output data. Some additional software was written to accommodate the requirements of this particular application.

Basically, the system performed well and produced strong correlation peaks distributed as predicted. However, the behavior of the photoplastic filter proved to be erratic and prevented a satisfying demonstration of totally automatic operation. The cause of this erratic behavior was identifed and a promising solution defined. This solution has not yet been successfully implemented, but it is being pursued in related efforts.

INPUT DATA

The input data for this experiment consists of two sets of abstract representations of sequential scenes from an orbiting space craft. Figures 11 and 12. They contain various patterns whose position and/or orientation change from frame to frame. These patterns represent the motion of objects such as clouds, ice, and oil slicks relative to a fixed background such as land masses.

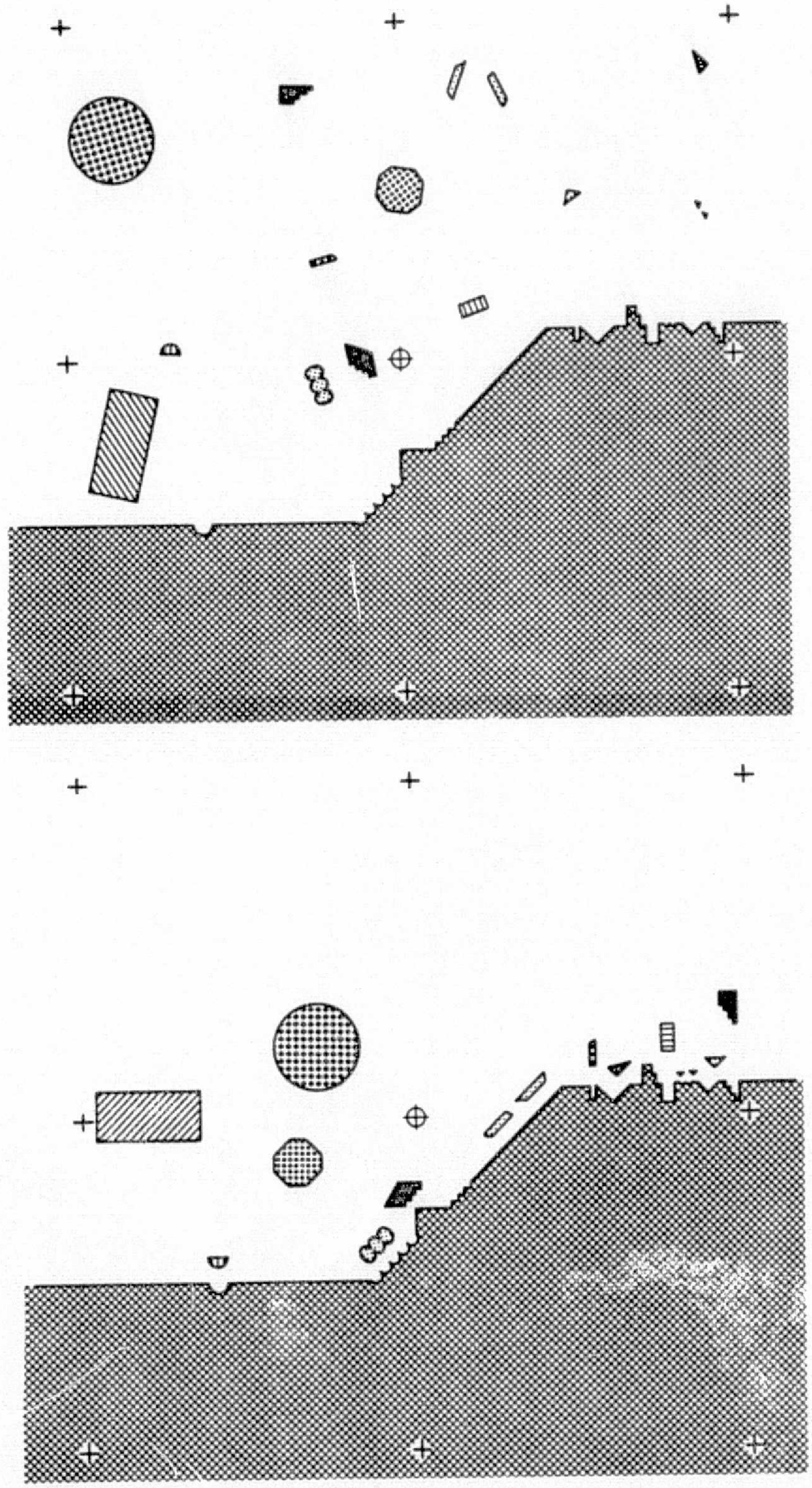

FIGURE 11. SIMULATED SHORELINE.

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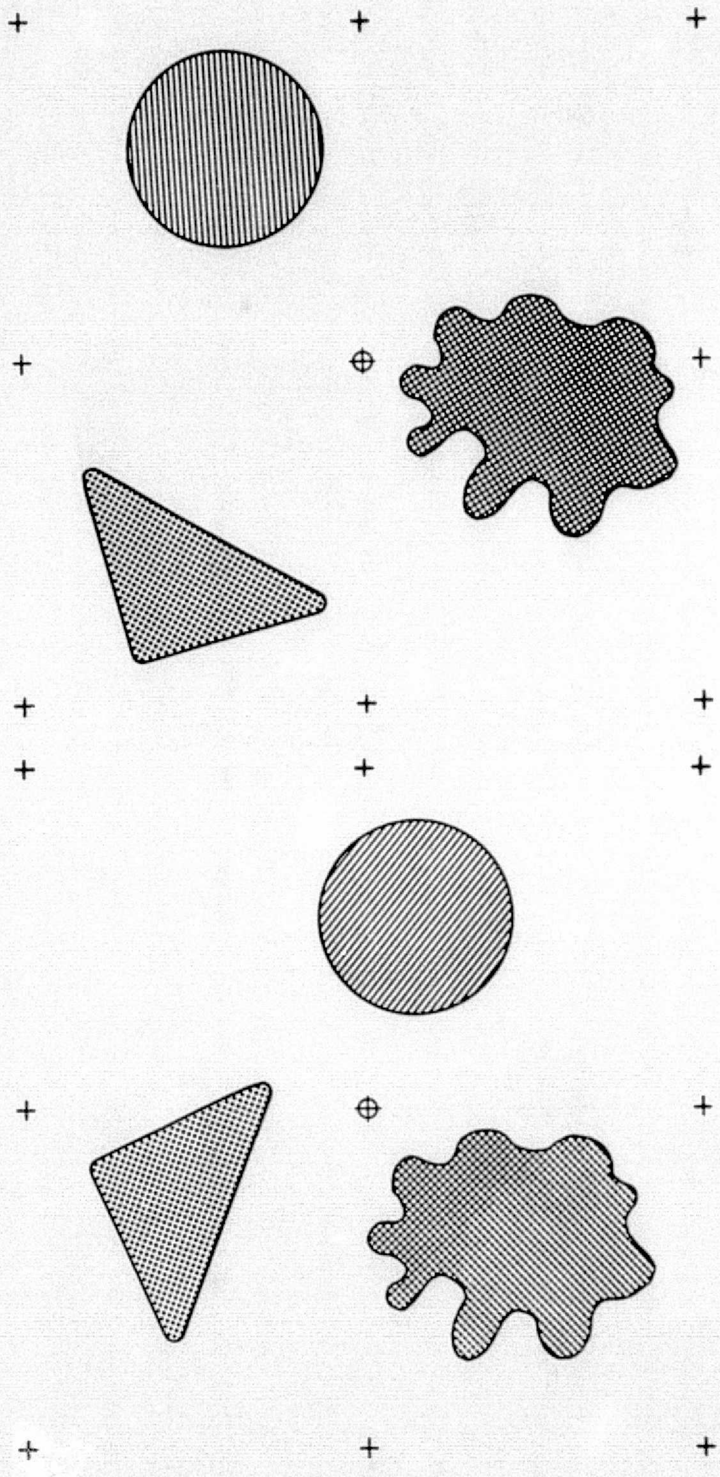


FIGURE 12. GEOMETRIC OBJECTS.

In order to minimize the search time that would be required with the present, rather slow operation of some of the laboratory system devices, we used the original scenes to make a new set of pictures with only translation or rotation of a limited number of objects. A sequency of three frames, Figure 13, was made on 70 mm film showing translation of a large rectangle, a medium size octagon and a small triangle. The relative areas of these objects are approximately 40, 15, and 1 respectively. The several other objects in the scene are stationary. A sequence of seven frames was made in which the large rectangle was rotated approximately 5^0 between frames, but not translated. The other objects remained stationary.

The 70 mm precision film gate was used to locate these frames sequentially at the input plane of the optical system. Normally the operator manually advanced the film to the first frame and then turned control over to the computer.

SYSTEM OPERATION

The laboratory processor was programmed to perform the following operations automatically:

1. Translate the scanning aperture mask to its extreme position; this totally uncovers the input scene.

2. Set the ratio of reference to signal beam intensities to a previously specified value.

3. Heat the photoplastic in order to erase it and then wait for the photoplastic to cool.

4. Turn on the corona device to charge the photoplastic and then open both shutters to expose a spatial filter.

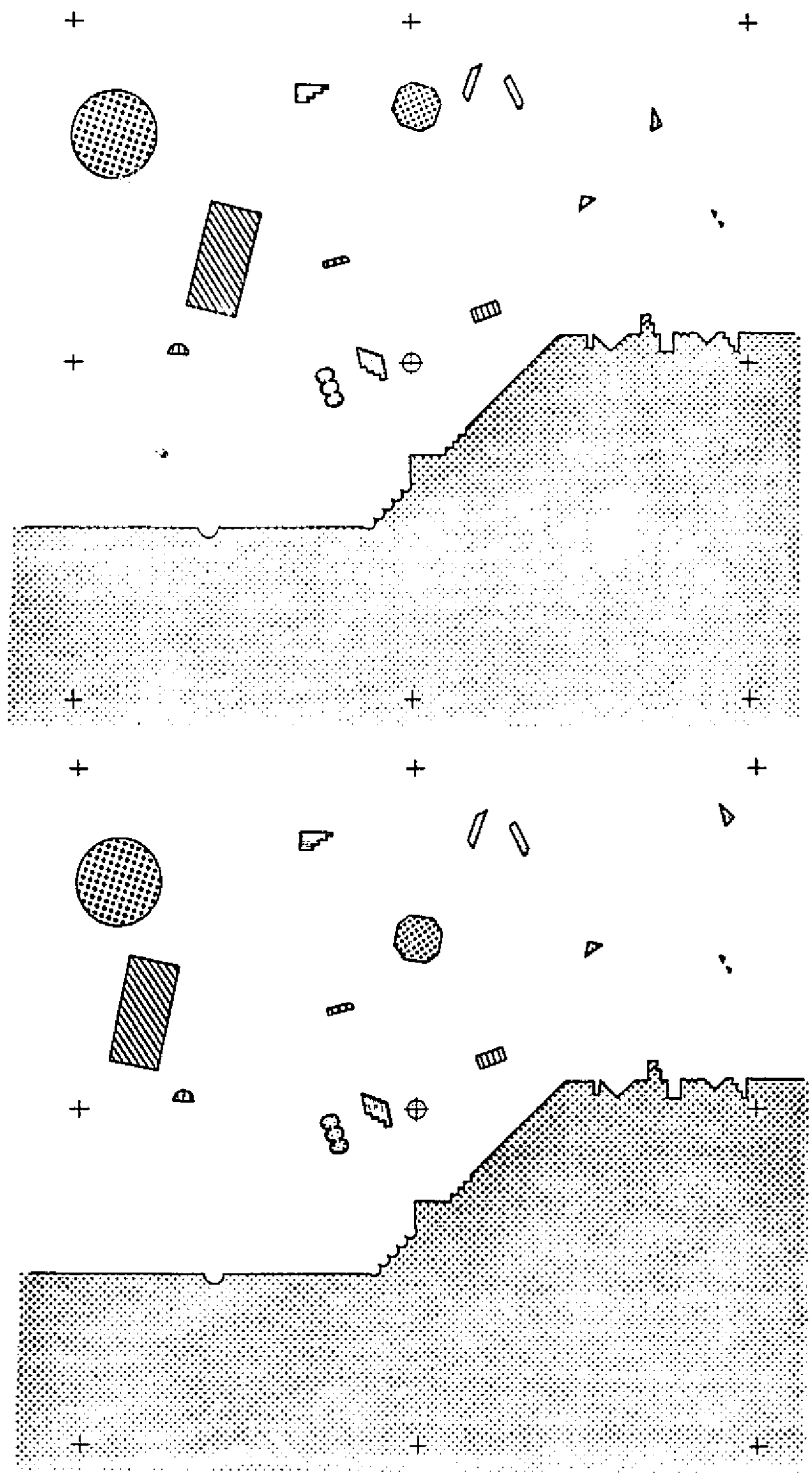


FIGURE 13. SIMULATED SHORELINE: TRANSLATION ONLY.

5. Close the shutters, recharge and then heat the photoplastic to develop the relief image.

The exposure and heating times as well as the desired K-ratio are initially typed in by the operator. After recording a filter, the system then automatically proceeds with the correlation search routine below.[6]

6. The film is advanced to the next frame, the scanning aperture is positioned at one corner of the frame, the signal beam shutter opened, and the image rotator oriented at some initial angle. The correlation of most of the objects involved was highly orientation sensitive, say $\pm 1^{\circ}$ to the -3 dB point. Consequently, an angular search was always performed on limits defined by the operator, say from -4° to $+4^{\circ}$ in 2° increments.

7. The scanning aperture is stepped through an N x N array of locations (N is operator specified) and correlation peak data are collected at each position of the scanning beam. Correlation peaks are detected by the TV-cell generator-computer readout system which determines the location of the brightest spot in the output. If that spot's intensity exceeds an operator specified minimum threshold, the computer prints out the location of the scanning aperture, the location of the correlation peak, the highest threshold (0 to 10) exceeded by the peak, and the angle of the image rotator. The correlation peak located is determined on the basis of an 8 x 8 cell array generated by the TV-computer interface.

At each position of the scanning beam, data was collected for each of several specified angles (e.g., -4°, -2°, 0°, $+2^{\circ}$, $+4^{\circ}$). The angle at which a correlation was detected was included in the printout.

If no correlation peak exceeds minimum threshold, no output is produced. If more than one peak (cell) exceeds the greatest threshold, the

number of peaks and the location of the scanning aperture is printed, but not the correlation locations since these are presumed to be false alarms.

8. When all locations have been processed at all angles, the operator can direct the system to make a new filter and then advance to the next frame and repeat steps 1 through 7 or he can omit the filter making operation and simply cross correlate arbitrary pairs of scenes (i.e., first and third, etc.). Alternatively, the system was programmed to proceed with subsequent filter generation and data collection without operator intervention.

GENERAL RESULTS

The system, with the exception of the photoplastic filter, performed as desired. All components functioned properly, and the TV-computer read-out system did a good job of detecting correlation peaks. However, because of erratic behavior on the part of the photoplastic device, truly satisfying automatic performance was not obtained. Moreover, the lack of any facility for normalization made it difficult to distinguish between correct and spurious correlations.

Some extremely good spatial filters were recorded in the photoplastic under computer control. These filters had high diffraction efficiency and a very good signal-to-noise ratio. They produced excellent correlations from all but the smallest objects (two small solid triangles). The location of these correlation peaks, as observed on the TV monitor, did indeed correspond to the displacement of the objects being correlated.

The auto correlation of any given object usually produced the brightest peak in the output; however, some cross-correlations (i.e. correlations with a different object), were quite strong, especially in the case of small, simple objects. This occurred because portions of these objects matched certain

features of other objects. For example, a small narrow rectangle might produce a significant correlation with the corner and edges of a larger rectangle. In one case, the width of a narrow rectangular object matched the spacing of the shading lines in a large object and produced a multiplicity of strong cross correlations. A more complex pattern is less likely to produce strong false correlation peaks than is a simpler pattern. Most of the patterns in these scenes are relatively simple, and, therefore, the probability of false alarms may be relatively large.

This situation was complicated by the fact that not all lines in the transparencies were equally transmissive and the system did not have any means for normalization. If a pattern matched a highly transmissive portion of a different object, a strong cross correlation resulted. This cross correlation could exceed the auto correlation peak if the desired pattern had lines of relatively low transmission. In order to minimize false alarms caused in this manner, a system must have some means for effecting normalization based on the reference and correlation signals.

Although the photoplastic filter often produced excellent results, it would seldom perform correctly twice in a row. In fact, approximately one filter in three or four tries was good at best. While this performance may actually be adequate in a manual, laboratory situation, it is unacceptable for truly automatic performance.

Two primary problems remain to be solved in order to produce a totally automatic system with acceptable hit and miss rates. These are normalization and consistent performance of the photoplastic filter. Normalization can be implemented by a number of hardware-software schemes. Basically, it involves monitoring the energy associated with local regions of

the input and reference scenes and using this information to correct the local light intensity in the output. While this problem may not be trivial by any means, we will not dwell on it further in this report.

The inconsistent performance of the filter appears to be caused by inprecise heating during the development operation. This problem may be solved by implementing a suitable closed-loop control on photoplastic heating. This problem was pursued in at least two other studies. In fact, this report was delayed for a considerable period of time in the hope that a consistent large area photoplastic device might become available as a result of these other efforts.[5,6]

It should be pointed out that we have obtained excellent and consistent results with photoplastic devices whose active area is small compared to the substrate. The problem of inconsistent performance is associated primarily with photoplastic devices having a large active area. In our laboratory system, we require a relatively large active area for recording spatial filters. Because of the importance of this problem, it is discussed extensively in Section VI.

SECTION VI

PHOTOPLASTICS

The basic problem in obtaining consistent performance in photoplastics appears to be precise temperature control of the photoplastic device during development. This operation is very critical. The temperature of the device must be raised to a point where the thermoplastic material becomes soft enough for the charge-induced fields to distort the surface. However, it cannot be made too hot, or held at this temperature too long; otherwise, charge redistribution occurs and no meaningful surface relief is obtained. This problem is most severe in the relatively large photoplastic devices we use in spatial filtering operations. These photoplastic devices have an active area ranging from $1\frac{1}{2}$ to 2 cm square, which covers most of the substrate surface. Since the active area of the device is so large, heating of the substrate is significant. In other photoplastic devices we are using for the holographic recording of digital data, the active area may only be a few millimeters square, and the substrate much larger. Substrate heating does not appear to be a problem and these devices behave in a very predictable and repeatable manner.

In this section we will discuss the basic properties of photoplastics, difficulties presently experienced with large area photoplastics, and potential solutions to these problems. During the time span of the study reported in this document, we attempted to implement what appeared to us to be the most promising solution to the probl of photoplastic inconsistency. While our approach seems sound and some progress was made, a completely successful solution to the problem has not yet been demonstrated.

BASIC PRINCIPLES OF PHOTOPLASTIC RECORDING

Photoplastic spatial filters (holograms) are formed as surface deformations in a thin layer of thermoplastic. A typical photoplastic device is shown in cross section in Figure 14. The substrate, optical glass, is coated with a thin, transparent conductor such as indium oxide. Two more layers complete the device: a photoconductor (poly-N-vinyl carbazole) and a thermoplastic (F Stabelite).

The sequence of operations in making a photoplastic recording of a light intensity pattern are shown in Figure 15. There are five steps involved. First, a static electric charge is deposited on the thermoplastic layer by means of a corona discharge device. (Typically, a fine wire at a potential of 5 to 10 kilovolts and partially surrounded by a cylindrical ground plane is used to create the corona.) Exposing the device to a pattern of light creates carriers in the photoconductor as a function of the local light intensity. These carriers fall through the potential gradient that exists in the photoconductor and locally reduce the potential at the upper surface of the thermoplastic. The electric field in the thermoplastic remains unchanged.

A second charge is deposited by reapplication of the corona discharge. This increases the electric field in the thermoplastic where the photoconductor has been exposed to light. The desired surface relief of the thermoplastic is then obtained by heating the thermoplastic to its glass transition temperature (i. e. where plastic deformation begins).

The thermoplastic deforms by becoming thinner in regions of higher electric field -- those areas receiving greater light intensity during exposure. Once an optimum deformation is obtained, the thermoplastic is cooled to freeze and retain the surface relief. This step is critical and difficult to control.

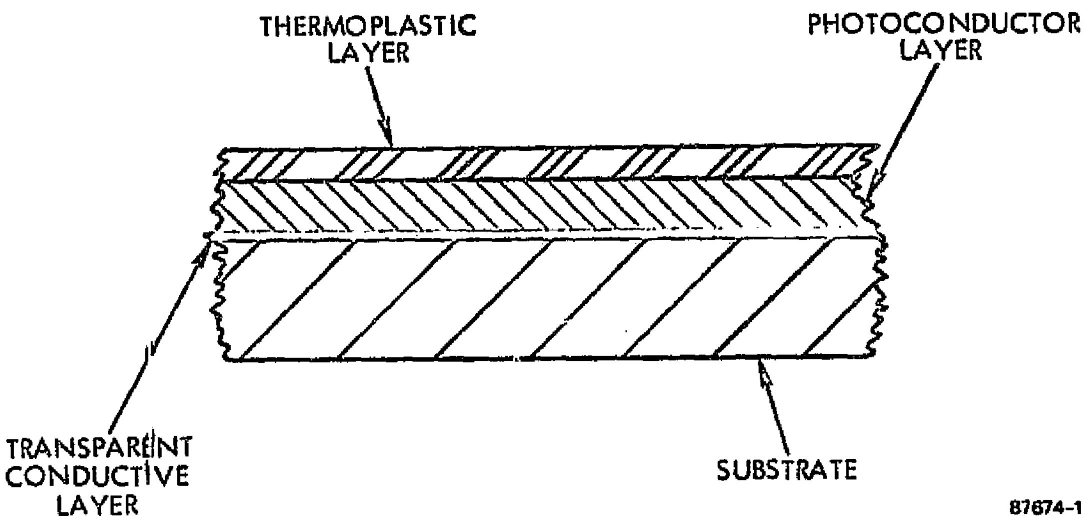


FIGURE 14. CONSTRUCTION OF EOO PHOTOPLASTIC FILM.

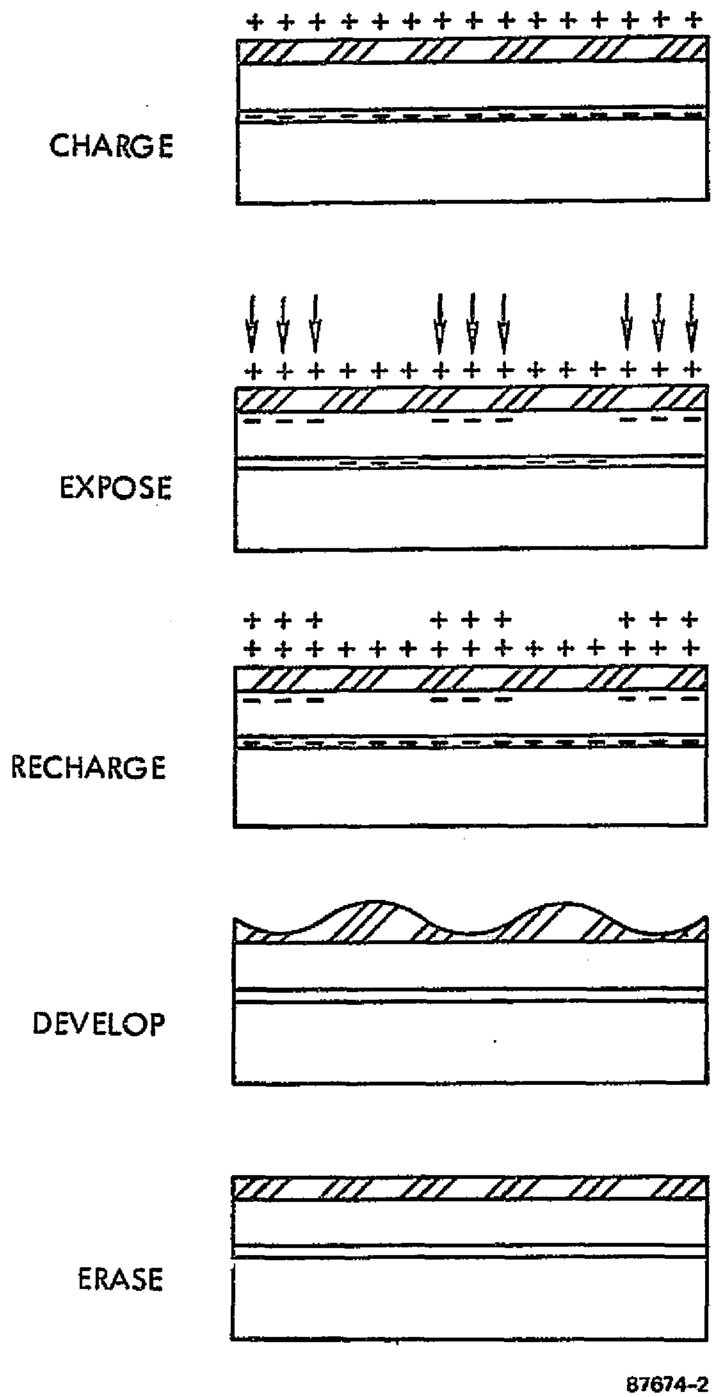


FIGURE 15. SCHEMATIC REPRESENTATION OF THE INFORMATION STORAGE PROCESS IN EOO PHOTOPLASTIC FILM.

In actual practice, a short heat pulse raises the thermoplastic above the plastic flow temperature; withdrawl of the pulse allows the film to cool. This heating is accomplished by passing a current through the transparent conductive layer. It could also be done by a hot air gun, CO_2 laser, oven, etc. When the thermoplastic has cooled below the plastic flow temperature, it can be used as a phase hologram. It is not light sensitive, but should not be exposed to high temperatures.

In order to reuse a photoplastic device, it is erased by applying a heating pulse several times longer than that used for development. The higher temperature in the photoconductor and thermoplastic results in a discharge of most stored charge due to increased conductivity. Control of this heating operation is not nearly as critical as that required for development. However, the film can be destroyed by excessive heat.

LARGE AREA PHOTOPLASTICS

We have successfully employed photoplastic devices with small active areas (say 5 mm x 5 mm) for holographic recording and they have worked very well. These small devices have been recycled a number of times with very consistent results. While the active area of these photoplastics is small, their glass substrates are comparitively large, typically 50 x 50 x 6 mm. Devices with a number of independently addressable small pads have also been used successfully.

As discussed in this report, we have also made spatial filters on photoplastic devices. These filters have performed well in terms of signal-to-noise and diffraction efficiency. Photoplastic filters have produced good results in optical word and character recognition experiments as well as

similar applications. Their convenience is a great help in a laboratory enviornment; however, a more significant advantage in an operational system is their compatibility with purely electronic control. Potentially, photoplastic filters can be contrclled by a computer in a purely automatic manner. However, in order to do this, the photoplastic device must be extremely consistent in its performance (i. e. its response to heating and charging signals).

In recording spatial filters, we have typically used photoplastic devices with large active areas (20 mm x 20 mm) and have experienced difficulty in obtaining consistent behavior. The cause of this problem appears to be uncertainty in the ultimate temperature achieved; this uncertainity is caused by changes in the substrate or ambient temperature. Normally, the device is heated to the desired temperature by applying a voltage pulse of known duration and amplitude. If the device is initially at the proper temperature (ambient), this method works quite well. However, after several cycles, the device substrate begins to get warmer and overheating occurs if the same fixed heating pulse is applied. This situation is complicated by any changes in ambient temperature.

Inconsistent performance by photoplastic spatial filters significantly affects their utility in an operational, automatic system. The most promising approach to solving this problem and realizing the operational potential of photoplastic spatial filters is to employ a closed-loop control system which responds to the instantaneous temperature of the thermoplastic layer. Such a closed-loop control must employ a method for sensing the temperature of the thermoplastic and must cut off heating when the temperature has reached the desired level.

An attractive solution for sensing the photoplastic device temperature is the use of a high speed thermistor incorporated in the thermoplastic layer itself. This method provides the most efficient heat transfer to the sensor, it is compact, and the thermistor could be literally made a permanent part of the photoplastic device. Similarly, the thermistor could be mounted on a mechanical finger and pressed into the thermoplastic layer. This provides potential reusability of the thermistor with different photoplastic devices and can offer good thermal characteristics. It might also be possible to monitor the resistivity of a region of the photoconductive layer which is not on a transparent conductor, instead of using a thermistor.

A preliminary, open-loop experiment was performed to evaluate the usefulness of starting the photoplastic heating cycle from a fixed initial temperature. A device with a 50 x 50 x 6 mm substrate and a 20 x 20 mm active area was used to record spatial filters in the usual manner. A relatively large thermistor bead approximately 1 mm in diameter was attached to the active area by means of heat sinking compount. The resistance of the thermistor was monitored by means of a digital ohmmeter.

The resistance of the thermistor was used to indicate the temperature of the photoplastic. The device was charged and erased in the usual manner. The temperature excursion of the photoplastic was followed by that of the thermistor resistance. The duration of the develop heating pulse was varied until an optimum was found, say 28 msec at 150V.

A number of spatial filters were recorded sequentially using develop heating pulses of this same duration and amplitude. These were recorded in the usual manner with the exception that the develop pulse was always started when the thermistor resistance indicated the photoplastic device was at a specific temperature somewhat above ambient. We found

that this method produced considerably more consistent results than simply waiting a fixed time between cycles, as is typically done.

Unfortunately, while these results were an improvement in consistency, they still left a great deal to be desired. We found that there was still a low probability (less than 0.5) that two sequential filters would be good. Moreover, as the ambient temperature rose from 70°F to 80°F, results became more unpredictable.

This experiment showed that even open loop temperature control provided some improvement in the consistency of holographic recording.

In a related effort,[6] we built a thermistor control circuit designed to cut off the heating pulse to the photoplastic device when either of two present temperatures were reached for development or erasure. This circuit was built and tested and operated properly. However, in order to obtain the required fast response, it was necessary to use very small thermistors. We obtained several thermistors with suitable time response and planned to hold them in intimate contact with the thermoplastic layer by mounting them on the end of a small plastic finger. Unfortunately, these very small thermistors were extremely fragile and were broken while trying to mount and use them.

Although these efforts were unsuccessful, greater care and the development of the necessary skills and experience should allow successful fabrication of photoplastic-thermistor devices. While this could not be accomplished within the time frame of this study, several points can be made:

1. The basic approach of closed-loop control is very desirable where larger photoplastic devices are concerned.

2. Small thermistors appear to be the most economical and simple temperature sensing method presently available. IR type sensors might be used, but they could be considerably more expensive.

3. Handling and mounting small and delicate thermistors is presently a problem, but the necessary skills and techniques should not be difficult to develop.

4. It may be practical to incorporate a temperature sensing element in the photoplastic device itself. This could be in the form of a thin layer with temperature sensitive conductor, forming a strip in close proximity to the active area of the photoplastic.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

The basic concept of using coherent optical processing techniques for object motion analysis appears feasible; however, some technological improvements are necessary before a fully automatic, operational system could be built. In particular, the problem of recording spatial filters in real-time must be adequately solved. In the near term, photoplastics appear to be one of the most promising means for the real-time recording of filters where modest recording rates are involved. Several approaches exist for the solution of problems presently associated with photoplastics and it seems likely that their performance can be improved with modest effort.

The ultimate decision of whether to use optical or digital means for object motion analysis must be decided on an overall system basis considering the problems of data input, processor function and data extraction. However, an optical approach is particularly attractive where images of large information content (many pixels) and arbitrary motion -- especially rotation -- are involved. A familiarity and appreciation of both digital and optical techniques is required to make an intelligent choice between them in a particular application.

REFERENCES

1. Vander Lugt, A., "IRE Transactions on Information Theory," IT-10, p. 139 (1964).

2. Vander Lugt, A. and F. B. Rotz, Applied Optics, 9, p. 215, (Jan. 1970).

3. Feinleib, J. and D. S. Oliver, Applied Optics, 11, p. 2752, (Dec. 1972).

4. For example:

   Maldonado, J. R., and A. H. Meitzler, "Strain Biased Ferroelectric Photoconductor Image Storage & Display Device," Proc. IEEE, 59, #3, pp. 368-382, (March 1971).

   Meitzler, A. H. et.al., "Image Storage Using Fine Grain Ferroelectric Ceramics," Bell System Technical Journal, July-Aug. 1970, pp. 953-967.

   Keneman, S. A. et.al., "Storage of Holograms in a Ferroelectric Photoconductor Device," Applied Physics Letters, 17 #4, pp. 173-175, (Aug. 1970).

   Groh, G. and G. Marie, "Information Input in an Optical Pattern Recognition System Using a Relay Tube Based on the Pockels Effect," Optical Communications, 2 #3, pp. 133-135, (Aug. 1970).

5. Holographic Recording Materials, Final Technical Report, Contract No. F30602-74-C-0030, RADC, July 1974, prepared by Electro-Optics Operation, Electronic Systems Division, Harris Corporation.

6. Optical Data Processing for Terminal Guidance, Final Technical Report - 1325-F-1, Contract No. DAAH01-73-C-0890, for the U. S. Army Missile Command, Aug. 1974, prepared by Electro-Optics Operation, Electronic Systems Division, Harris Corporation.

APPENDIX 1

SAMPLE EXPERIMENT

The pair of scenes shown in Figure A-1 were used for an object motion analysis experiment with laboratory system operating in an automatic mode. The operator entered the desired K-ratio and exposure time; the system then automatically made a photoplastic filter with input A-1a, advanced to the next frame (A-1b), and searched for correlation peaks.

A typical printout produced by the computer is shown in Table A-1. This data has been retyped to improve the format, but the numerical values are unchanged. The heading indicates a photoplastic filter was made under computer control with a K-ratio of 7 and an exposure of 350 ms. The threshold value of 0 means that any correlation peak exceeding a threshold of 0 (least light level) will be cataloged. The image is to be rotated from -2^{o} to $+2^{o}$ in 2^{o} increments and the moving aperture is stepped in eight intervals in each direction. Readings were made at X = 500, 638, 775, 913, 1050, 1188, 1325, 1463 and 1600 while Y assumed the values 1200, 1338, 1475, 1613, 1750, 1888, 2025 and 2163. The illumination beam was approximately 100 units in diameter. Consequently, samples overlapped and the illuminating beam was approximately the same size as the large circular object near 500, 1200.

The subsequent computer print out indicates the position of the scanning aperture, the angle of the image (produced by the image rotator), the value of the strongest correlation peak(s) detected and the cell(s) containing the peak(s). If more than two peaks are found, only the number of peaks and the x position values are printed (e.g. entries 2 and 3, Table A-1).

The TV-cell generator was programmed to produce an 8 x 8 cell array with cell 4, 5 taken as the center. This cell is suppressed by the computer software since it represents no motion.

The computer printout shows both correct detection of the motion of objects and a number of false alarms. In this example, only the large rectangle, the octagon, and a small triangle moved. The rectangle is translated downward while the octagon moved left and up. The motion of the rectangle is indicated in entry numbers 14, 17, 18, and 19. The position of the correlation peak is 4, 2 representing a 0, -3 cell shift from the center cell 4, 5. The octagon's motion is shown in entries 31, 32, and 33 where the correlation peak is reported at 3, 6 giving a -1, +1 shift. The motion of the small triangle was not detected.

A single cell shift of the correlation peak corresponds to a motion of approximately 100 units in the input. The motion of the rectangle has been correctly indicated. The octagon moved in a more horizontal direction than the -1, +1 shift implies. However, it did move in the correct general direction and approximately the distance indicated. Overall, these two correlation detections correspond reasonably well to the actual object motion. The primary source of error is the rather crude 8 x 8 cell array used to locate the correlation peaks.

The major problem in this particular example is the large number of false alarms indicated by all data entries other than those associated with the rectangle and octagon. In some cases, these false alarms were caused by an extremely strong correlation peak centered on cell 4, 5 (no motion) but having sidelobes spilling over into adjacent cells (e. g., entries 1-10). Other false alarms were caused by the edge of the frame (e. g., entries 35-40) or particularly strong linear features (entry 26). In some cases, the cause of a false alarm was not apparent.

TABLE A-1

EXPERIMENTAL RESULTS

K = 7, EXPOSURE = 350

THRESHOLD = 0; ANGLE = -2, 2, 2; STEP = 8

Index	Position X	Position Y	Angle	Peak Value	U	V
1	500	1200	-2	9	5	4
2	4 at 500			0		
3	3 at 500			0		
4	500	1338	2	9	7	6
5	638	1200	-2	9	7	6
				9	6	6
6	638	1200	0	9	7	6
					6	6
7	638	1200	2	9	6	6
8	5 at 638			0		
9	4 at 638			0		
10	3 at 638			0		
11	638	1613	-2	9	6	4
12	638	1613	0	9	6	4
13	638	1613	2	9	6	4
14	638	1750	-2	9	4	3
				9	4	2
15	3 at 638			0		
16	3 at 638			0		
17	638	1888	-2	9	4	2
18	638	1888	0	9	4	2
19	638	1888	2	9	4	2
20	913	1475	-2	9	4	5
21	913	1613	-2	9	5	4
22	913	1613	0	9	5	4

Index	Position X	Position Y	Angle	Peak Value	U	V
23	913	1613	2	9	5	4
24	913	1750	-2	9	5	4
					4	3
25	913	1750	0	9	5	4
					4	3
26	3 at 910			0		
27	1050	1338	-2	9	4	6
28	1050	1338	0	9	5	4
29	1050	1338	2	9	5	4
30	1050	1750	-2	9	3	4
31	1188	1338	-2	9	3	6
32	1188	1338	0	9	3	6
33	1188	1338	2	9	3	6
34	1600	1200	-2	9	7	5
35	1600	1200	0	9	7	5
					4	3
36	1600	1200	2	9	7	5
					4	3
37	1600	1338	0	9	7	5
					4	3
38	1600	1338	2	9	7	5
					4	3
39	1600	1475	-2	9	7	5
40	1600	1475	0	9	7	5
			2		4	3
41	1600	1475		9	7	5
					4	3

Index	Position X	Position Y	Angle	Peak Value	U	V
42	1600	1613	-2	9	7	5
43	1600	1613	0	9	7	5
					4	3
44	1600	1613	2	9	7	5
					4	3
45	1600	1750	-2	9	7	5
46	1600	1750	0	9	7	5
47	1600	1750	2	9	7	5
48	1600	1888	0	9	7	5
					4	3
49	1600	1888	2	9	7	5
					4	3

APPENDIX 2

CORRELATION OUTPUT FROM ARTIFICIAL SCENES

Correlation experiments were performed using the artificial scenes provided by the contractor. The reason for using artificial scenes rather than real satellite imagery was to provide accurate control over the input data so as to simplify subsequent analysis of the optical processor's output. While this approach initially appeared quite reasonable, it proved to be the source of some difficulty.

The patterns used in the simulated scenes created confusing results because of the peculiar nature of their cross-correlation functions. In general, objects in the scene contained cross-hatching which correlated strongly with all other cross-hatching and linear boundaries. The matched spatial filter actually cross-correlates edges and, in many cases, the total amount of energy associated with cross-hatching greatly exceeds that corresponding to the external and unique boundary of an object. Consequently, a great number of strong spurious cross-correlation peaks were generated by each object. Particularly damaging was the fact that as an object was rotated from its nominal position, its cross-hatching or linear boundaries would cross-correlate strongly with those of other objects. This is a case where the artificial scene used for simplicity actually produced a "worst case." The more truly random patterns occuring in nature represent a much more favorable situation.

Figure A-1 shows a pair of simulated shore scenes in which some objects have moved between frames. A transparency of A-1a was used to make a spatial filter in the usual manner using 649F photographic plates.

The auto-correlation of this entire scene is shown in Figure A-2a. The intense centeral core of the auto-correlation is surrounded by a strong, periodic pattern. This pattern is caused by the cross-hatching in various objects in the scene, particularly that of large "shore" area.

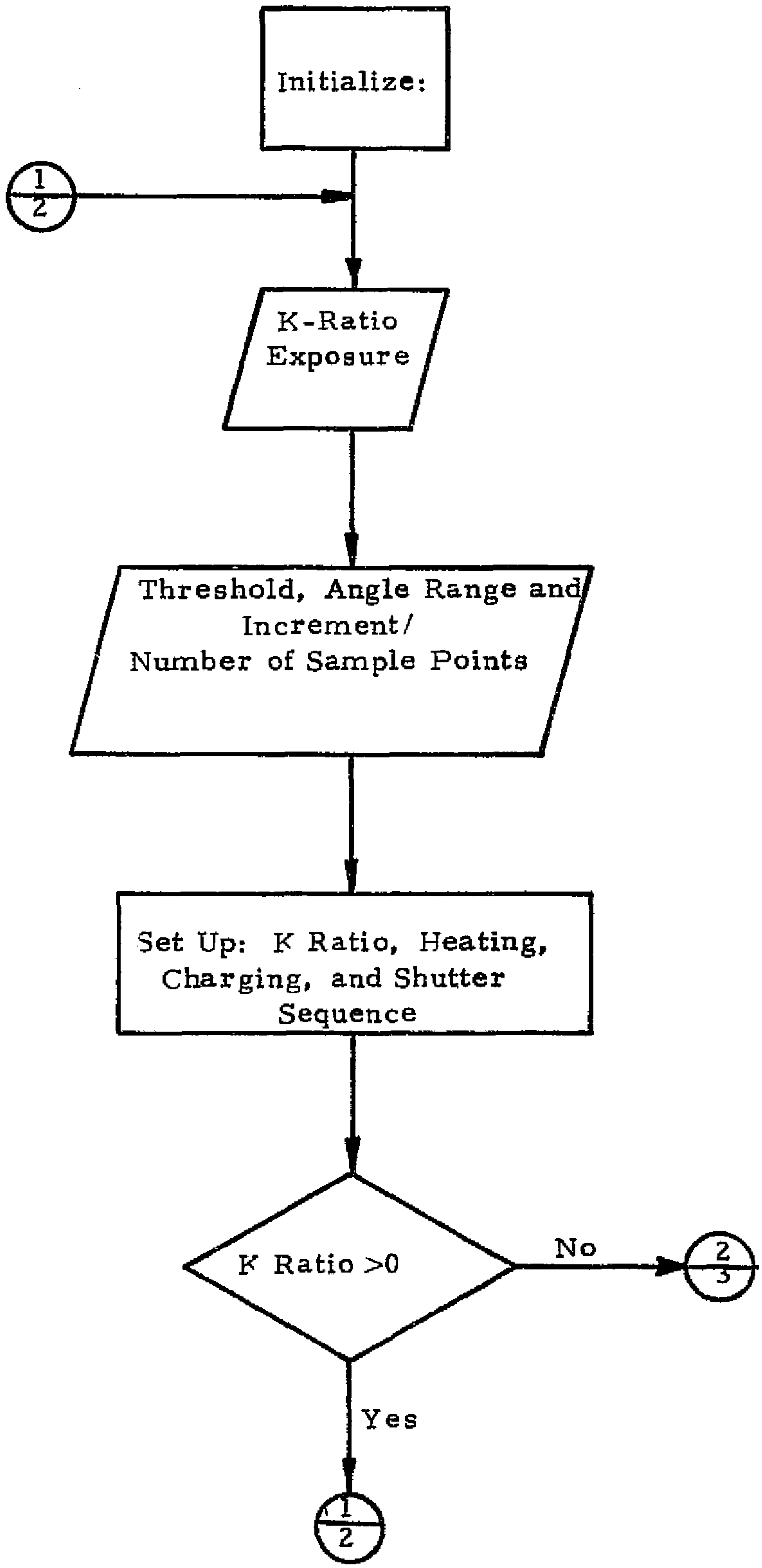
Figure A-2b shows the system output when only the large rectangular shape is illuminated. While the correlation peak has a small intense core, there is a considerable amount of energy spread in the direction of the long axis of the rectangle. The correlation has a periodic structure induced by the cross-hatching. It is interesting to compare this correlation pattern with those caused by clouds (Figure 8). In the latter the more generally random structure of the pattern produces a strong central pattern with practically no sidelobe structure.

When the rectangular object is rotated, the correlation changes. Typically, the intense core rapidly degenerates with angle while the sidelobe structure is affected to a lesser degree. This is shown in Figure A-2c where the large rectangle has been rotated 2°. The central peak is gone and significant cross-correlations with other objects are beginning to appear. Rather strong, spurious cross-correlations can result when the rectangle is rotated so that its long side or its cross-hatching lies parallel to a straight line. In fact, the dot shading on the "shore" cross-correlations strongly with the shading in the rectangle because the shading lines and dots have the same spacing. At the proper angle, a very extensive and strong false alarm is produced.

The effect of simple translations on the correlation of the rectangle is shown in Figure A-3a. This is a double exposure made in the system's output plane. Between exposures, the input transparency was moved a distance approximately equal to the width of the rectangle and at an angle of 45°. Only the rectangle was illuminated in both cases.

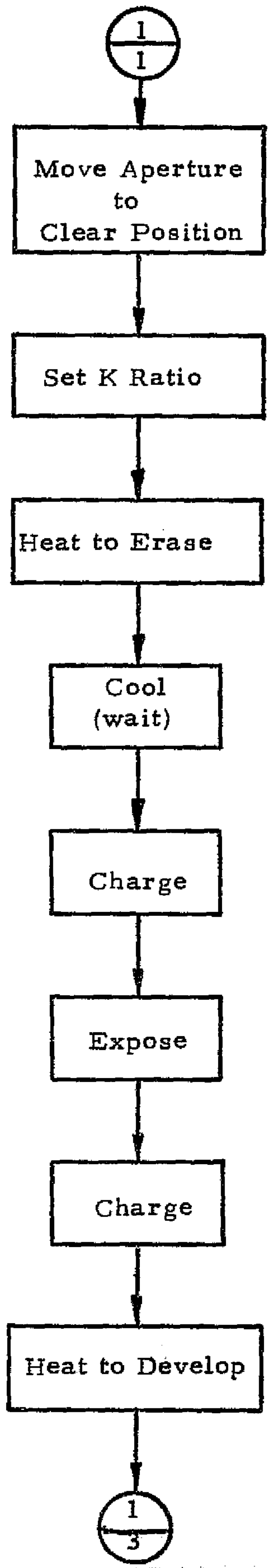
Figure A-3b is similar to A-3a except that the only large circular object is illuminated. The transparency was moved approximately twice the diameter of the object between exposures. The correlation of the circular object shows a particularly strong, regular sidelobe pattern. The cross-hatch in this case is actually a regular array of small, opaque squares. As in the case of the rectangle, the correlation peak has moved an amount directly proportional to the motion of the pattern in the input.

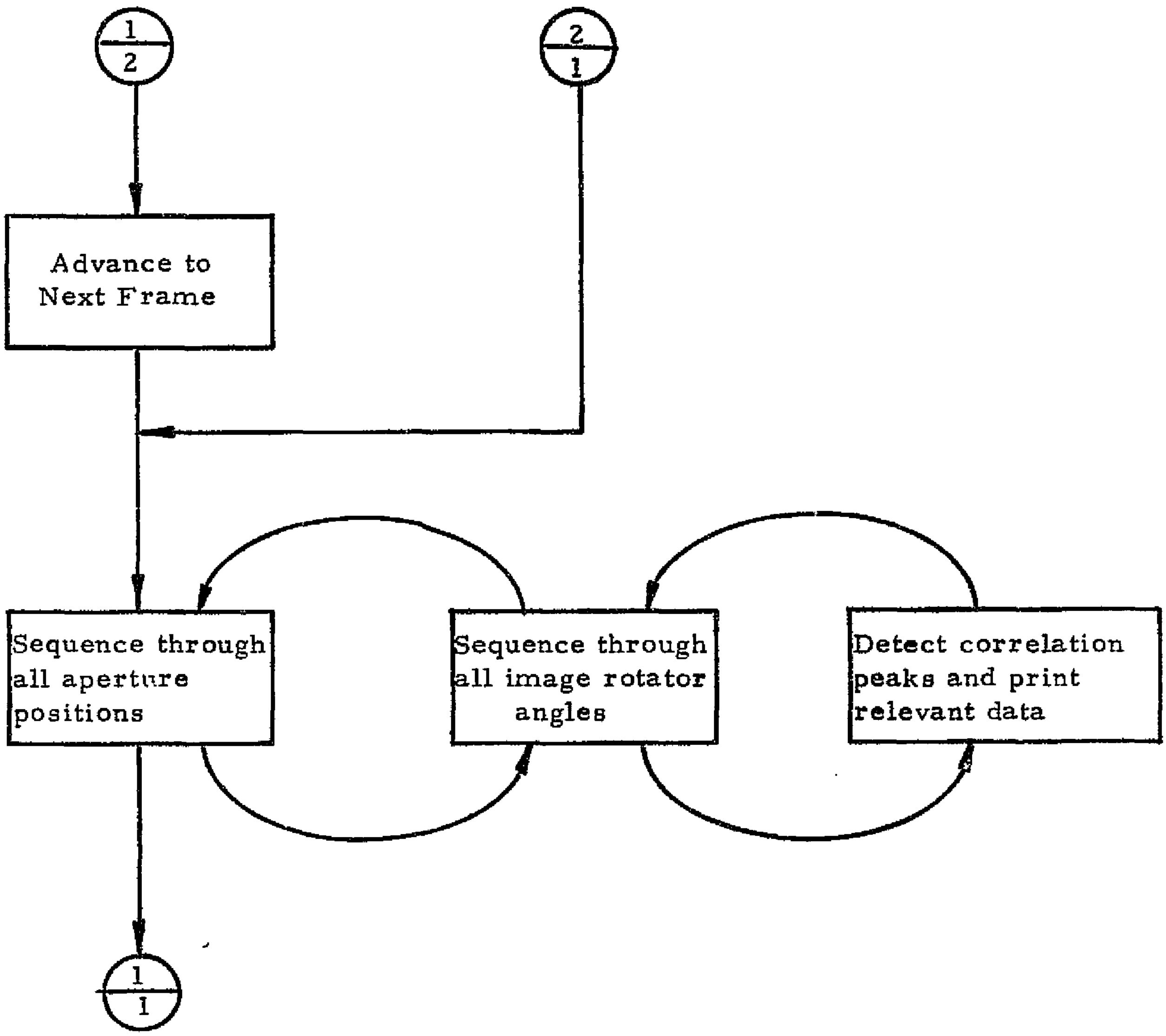
These figures show the motion of the correlation peak as a function of the position of the pattern in the input. However, they also illustrate the unusual and awkward nature of the auto-correlations involved. The strong, regular sidelobes appeared as false alarms to the relatively simple correlation peak detection system used. Natural patterns, such as clouds, tend to be fairly random and produce correlation peaks with a very strong central core and weak sidelobes (Figure 8).



Flow Chart: Object Motion Analysis

Photoplastic Sequence




1
2
2
1
Advance to Next Frame
Sequence through all aperture positions
Sequence through all image rotator angles
Detect correlation peaks and print relevant data
1
1

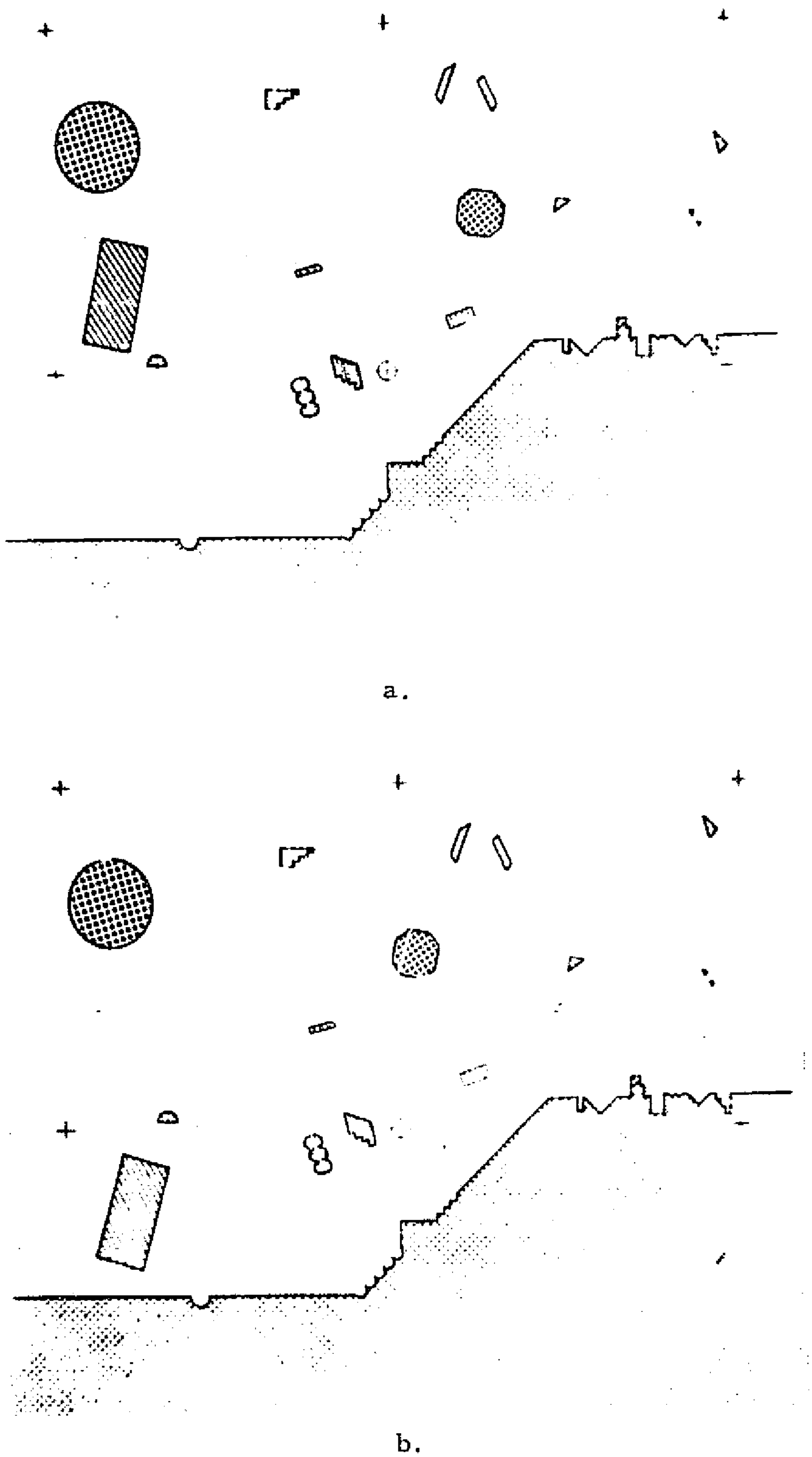
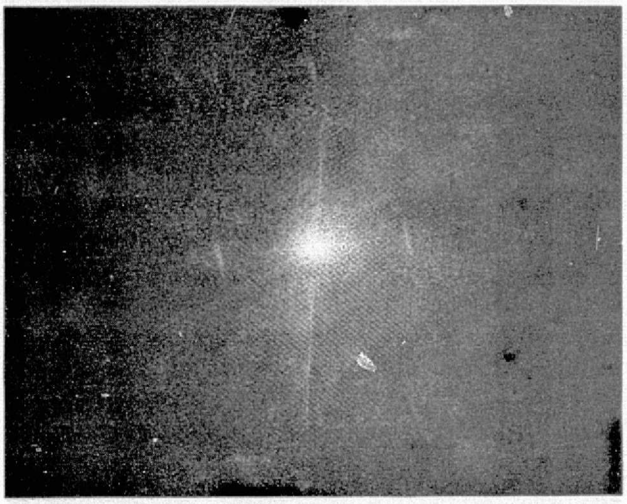
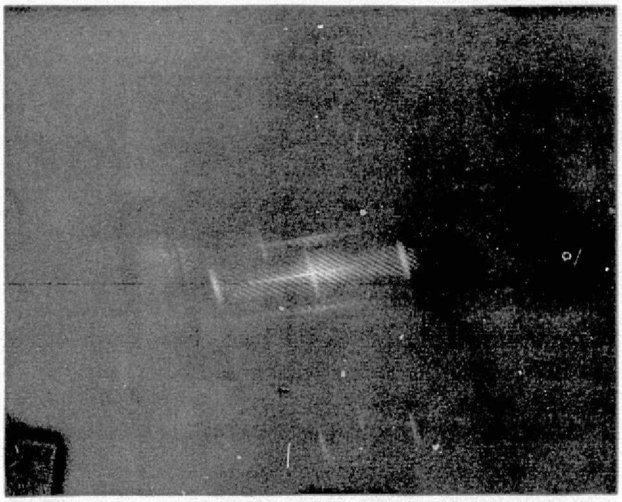


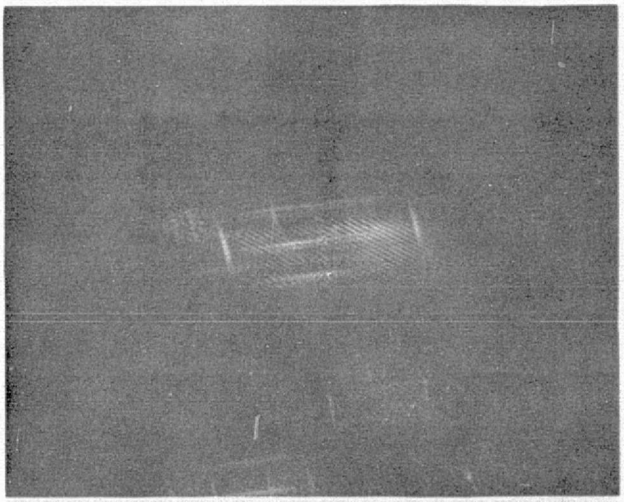
FIGURE A-1. SIMULATED SHORE SCENE



a. SCENE AUTO CORRELATION



b. RECTANGLE AUTO CORRELATION



c. RECTANGLE AUTO CORRELATION AT 2° ROTATION

FIGURE A-2. OPTICAL CORRELATOR OUTPUT

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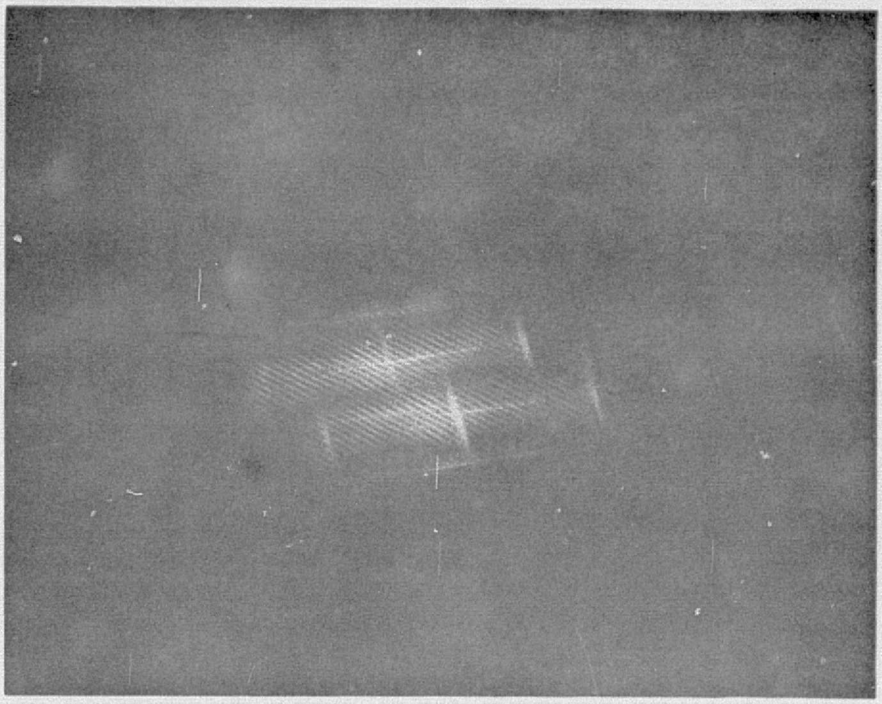
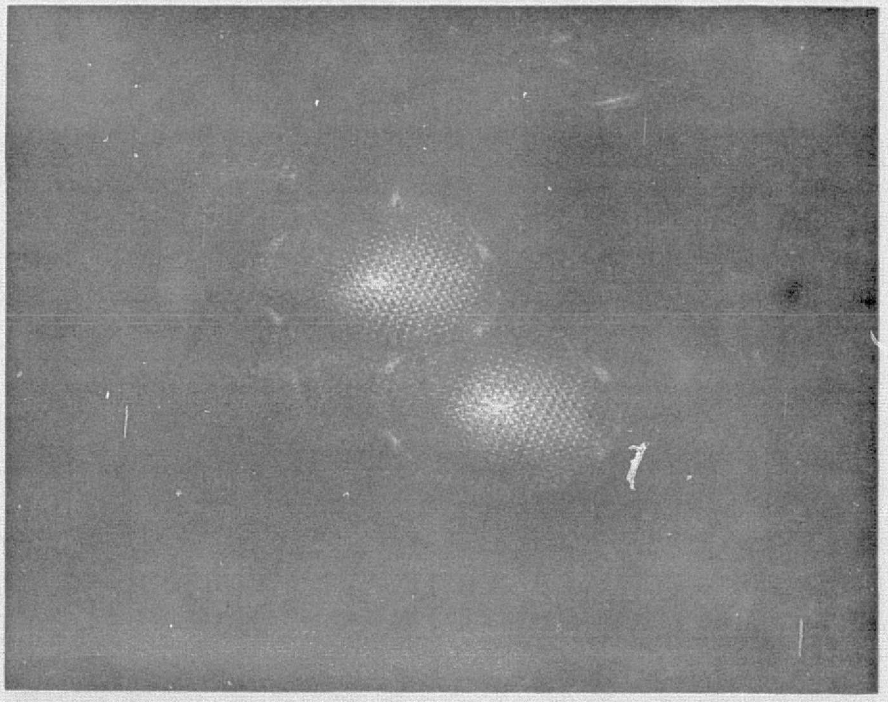
ELECTRO-OPTICS OPERATION



a. DOUBLE EXPOSURE WITH INPUT TRANSLATED AND RECTANGLE ILLUMINATED



b. DOUBLE EXPOSURE WITH INPUT TRANSLATED AND CIRCLE ILLUMINATED

FIGURE A-3. CORRELATION PEAK MOTION